

TRACTION INDUCTION DRIVE FOR RAILWAY

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Abstract. This paper presents the computer simulation and comprehensive dynamic processes of the induction motor with three-phase power inverter for traction application analysis. The control with proportional variation of amplitude and frequency of the power inverter are realized. The computer simulation of the considered traction drive on the basis of CASPOC software is executed. Computer CASPOC models of the induction motor, three-phase power inverter, control circuits and equivalent circuit of mechanical load are presented. Different control laws during acceleration of the traction induction drive and their influence on dynamic behaviour are researched. Transients of the traction induction drive with impulse and harmonic input voltage of the induction motor are compared. The procedure to design of the traction drive control with improving dynamic and power characteristics is offered.

Keyword: Induction motors, converter control, traction, simulation

Introduction

Currently, most suburban trains in Russia contain 2 head carriage, 5 - 6 motor carriage and 3 - 4 auxiliary carriage. Thus suburban train consists from 10 or 12 carriages. Each motor carriage of this train has DC traction drive included 4 DC motors with nominal output power 200 kW. Also the each traction drive contains 18 step power circuit breakers and power starting resistors, which carry out start-up and regulation of the train speed. Numerous efforts to use traction induction drive instead of obsolete and unserviceable DC motors with 18 step power circuit breakers with power starting resistors were not reliable.

Traction electric drive for railway application has to provide the adjustment of both rotor speed and electromagnetic torque according to the given machinist command (for example, soft start, rotor speed stabilization, electrodynamic braking, etc.). They demand of both motion modes control, dynamic losses reduction and the traction induction drive semi-conductor power elements instantaneous current value limitation [1...12].

The search of control laws poses the problem of drive dynamic characteristics research under different control ways and different loads, providing mentioned requirements. This problem could be effectively solved by computer simulation method. In this paper computer simulation of traction induction drive on the basis of the CASPOC software is offered, which is intended for modeling of electromechanical systems. The CASPOC software was chosen because of presence of unique resources such as special library macros for power electronic modeling, AC drives and mechanical loads, special block-diagram components for control systems modeling, interactive changing of component parameters during calculation and results displaying of real time scale.

Simulation of the traction induction drive

The considered traction AC drive consists of the traction induction motor with squirrel-cage rotor, three-phase power inverter and control system. Developed computer simulation of the traction AC drive is based on the module principle and represents the set of individual CASPOC models, which interact with each other in process of calculation, as in real devices. Macros of the embedded library of the CASPOC software are used as load-bearing elements (induction motor, transistor, diode, etc.). Computer CASPOC models of the control blocks including pulse-width modulation (PWM) and equivalent mechanical load are assembled according to the original circuits.

The CASPOC model of the power inverter (fig. 1) contains 6 power transistors (VT1...VT6) with reverse diodes (D1...D6) and input capacitor. The input values of the model are control voltage (G1...G6) of power transistors and voltage of the power supply (B1). The output values: output voltage of elements (LR, LS, LT), which are equivalent stator circuit of the traction induction motor.

Note: CASPOC doesn't allow to connect electronic circuit elements to block scheme elements, so output voltage of inverter arrives to equivalent stator circuit of the traction induction motor.

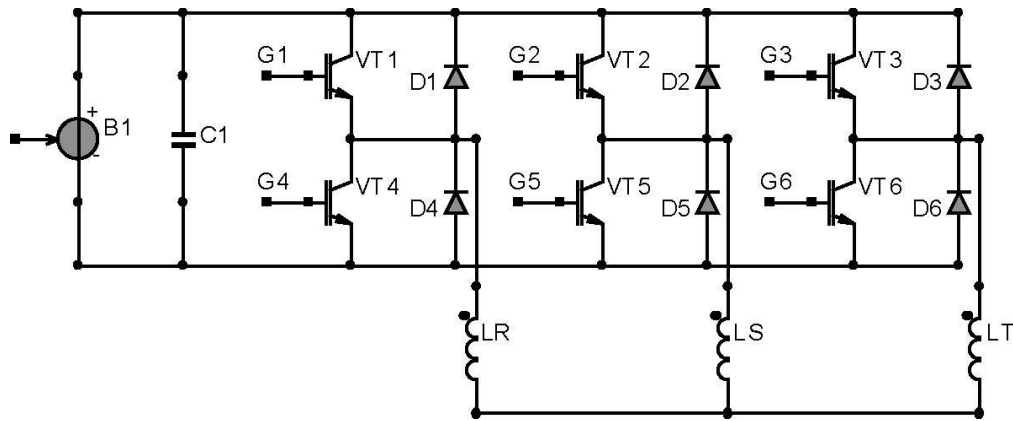


Fig.1: The model of the three-phase power inverter

The CASPOC model of traction induction motor and mechanical load is shown in fig. 2. It contains block ASMSC (equivalent power circuit of the induction motor), block LOAD (equivalent circuit of the mechanical load), blocks V(2)-V(8), V(3)-V(8) and V(4)-V(8) (indicate phase voltages of the ASMSC), blocks IR, IS and IT (indicate phase currents), blocks IC_E1, IC_E2 and IC_E3 (feedback to stator windings). The input values are phases voltage V(2)-V(8), V(3)-V(8) and V(4)-V(8), load torque (T_{load}), equivalent moment of inertia (J) of the rotor and load, stiction (f) and mutual inductance (L_m). The output values: rotor speed (ω) and electromagnetic torque (T_{input}) of the induction motor. It should be mentioned, that inductances' values are used in the model, hence it's possible to imitate the adjustment of supply voltage frequency.

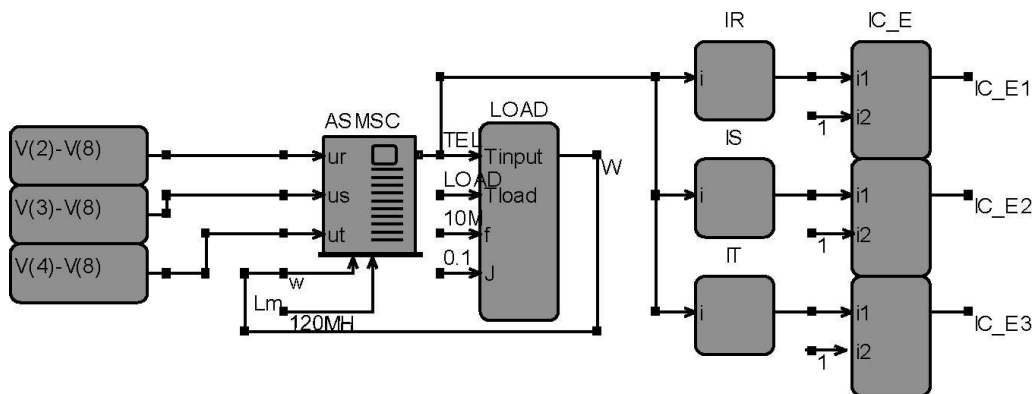


Fig. 2: The model of the induction motor and mechanical load

The model imitates of the current displacement effect is shown in fig. 3. It allows considering the rotor speed influence on the rotor active resistance ($R_r=R_r(\omega)$), so allows imitating the current displacement effect in rotor winding of induction motor. The considered model involves arithmetical blocks MUL, SUB, LIM and block CHANGEP, that allows changing a parameter of induction motor model ASMSC. The input value of model is rotor speed (ω). The output values: value rotor active resistance (CHANGEPI).

Control of the traction induction drive

Dynamic behavior essentially depends on control, which could be selected according to operation mode, having provided significant reduction of surge electromagnetic, mechanical and heat loads. In order to select of design parameters of the considered traction drive the method of dynamic behavior estimation under different control laws on basis of integral characteristics is offered. The method contains two stages. At first stage the control law is quested, it provides given operation mode requirements by dynamic parameters: runaway speed, limitation of starting current, acceleration softness, lack or limitation of torque rippling, etc. At second stage obtained transient characteristics of stator and rotor currents and torque are processed, so integral parameters are estimated.

In the model frequency adjustment from developed law is realized. Acceleration modes with linear time dependence of supply voltage frequency (t) are analysed, so the adjustment according to harmonic law with adjustment depth 20% nearby nominal mode is analysed.

The obtained dynamic characteristics allow designing empirical control laws for the tensest mode by energetic characteristics - load start of traction drive. Mechanical load considering active torque, dry and viscous friction is analysed. Limitation of starting current and torque rippling level and power consumption minimization is taken into account.

Offered control law looks like:

$$U = A + B f \sqrt{C + D f^2}$$

where A constant, which is defined by experience;

$$B = \frac{U_n}{f_n p} ; \quad C = \frac{X p^2}{M_n} ; \quad D = 4 \cdot Y (1 - s_n)^2$$

- U_n - nominal output phase voltage of the power inverter;
- f_n - nominal frequency output phase voltage of the power inverter;
- p - number of poles of the induction motor;
- X and Y - mechanical load factors;
- M_n - nominal output torque of the induction motor;
- s_n - nominal motor slip.

The CASPOC model that controls frequency and amplitude of the output voltage of the power inverter is shown in fig. 6. Amplitude variation is realized by signal applying to the controlled source of constant voltage. Frequency variation is realized by signal applying to the block that controls transistors.

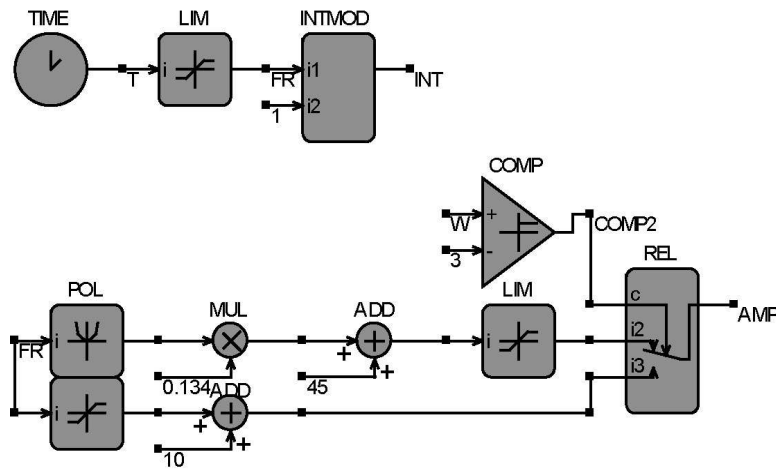


Fig. 6: The model that controls frequency and amplitude of the output voltage of the power inverter
Establishing time dependence of frequency is possible both as linear function and as more complex law.

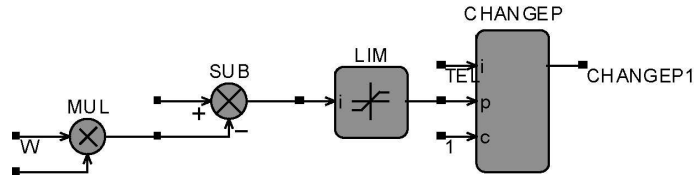


Fig. 3: The model imitates the current displacement effect

The CASPOC model imitating the mechanical load is shown in fig.4. This block imitates squared relationship of load moment at the traction motor shaft. Law of load variation:

$$M(w) = F_1 w + F_2 w^2,$$

where F_1 and F_2 - factors of mechanical load.

So dry friction: $M = M * sign(w)$ and active torque: M_L is realized in this model.

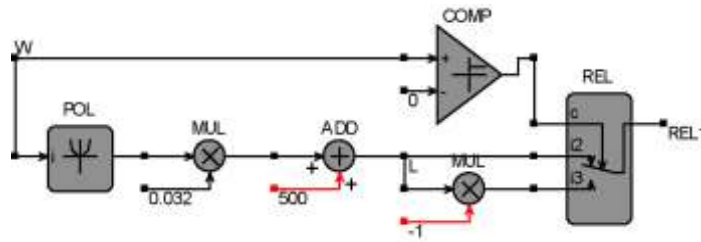


Fig.4: The model imitates the mechanical load

The CASPOC measure model of the output power of inverter and mechanical power of induction motor is shown in fig. 5. It allows estimating the value of loss depend upon rotor speed, that will allow concluding of effectiveness of one or another control.

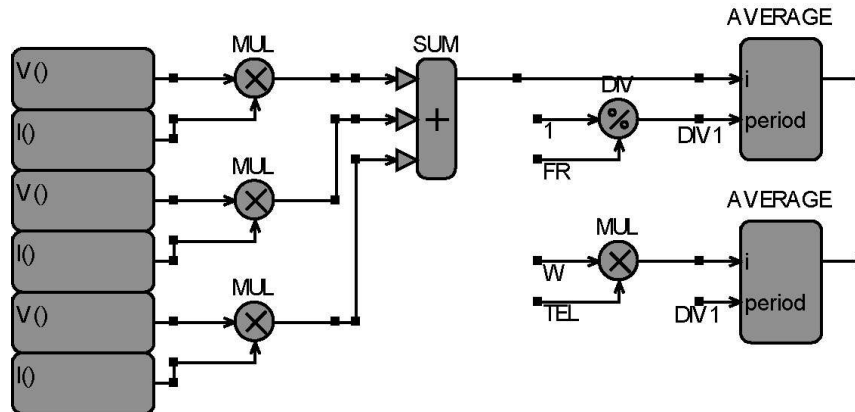


Fig. 5: The measure model of the output power of inverter and mechanical power of induction motor

The output power of inverter is defined as following:

$$P_1 = U_a I_a + U_b I_b + U_c I_c,$$

where U_a, U_b, U_c output phase voltage of the inverter;
 I_a, I_b, I_c output phase current of the inverter.

The mechanical power of the induction motor is calculate as following:

$$P_2 = T_{input} * w,$$

where T_{input} value of the electromagnetic torque of the induction motor;
 w the value of the rotor speed.

The results of the compute simulation

By using the proposed CASPOC model (fig. 7), the calculation is performed for traction induction drive. The traction drive parameters are $P_2=200\text{ kW}$, $U =2200\text{ V}$, $n=1500\text{ rpm}$, $p=2$, $\cos \varphi =0.92$, $\eta =0.94$, $s_n=0,016$. The task of control law research, supply voltage form influence on adjustment quality (steady state time, transients of electromagnetic torque and currents, reactive current appearing at transient).

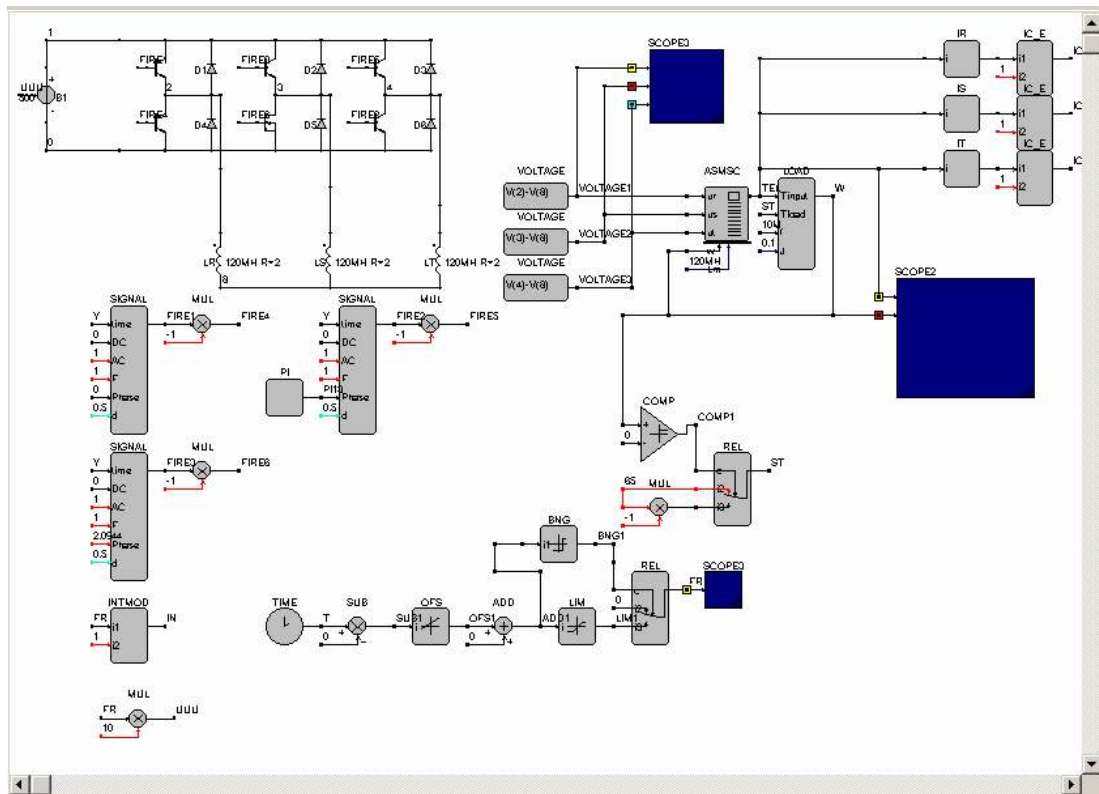


Fig. 7: The model of the traction induction drive

For the analysis of dynamic characteristics of the considered traction drive is chosen the traditional three-phase induction motor with nominal electrical values. The simulation results of transients (soft-start) and steady stator current of the induction motor, of the rotor speed w and electromagnetic torque T_{input} under frequency control with linear dependence between frequency and amplitude of input voltage are shown in fig.8 and fig 9.

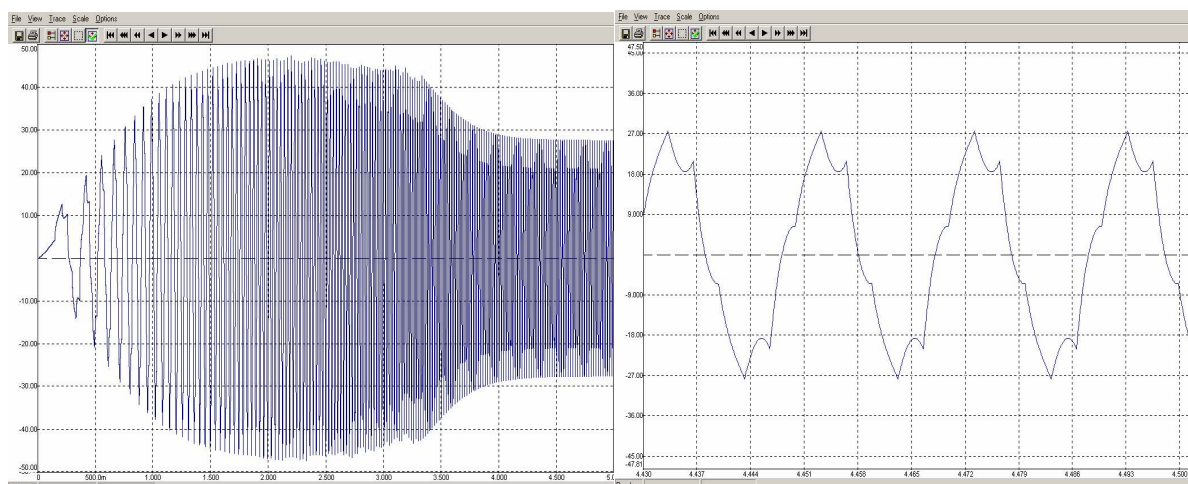


Fig. 8: The simulation results of transients and steady stator current of the induction motor

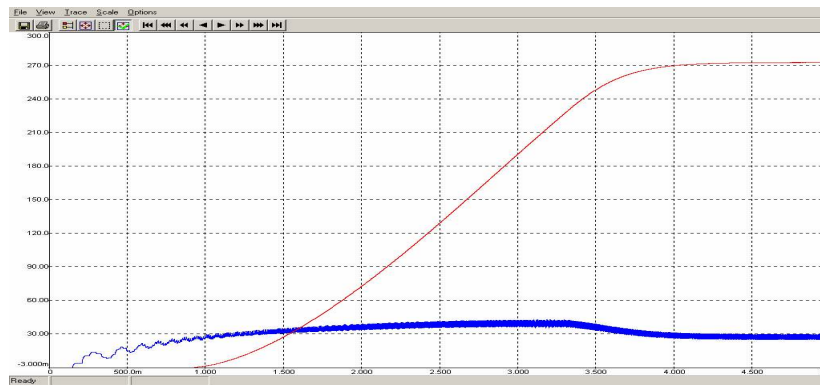


Fig. 9: The simulation results of the rotor speed w and electromagnetic torque T_{input}

The results of compute simulation allowed deducing empirical control laws for a number of important operating modes of the traction drive. That enabled to develop the method that allows synthesizing optimal control laws both in the view of dynamic behavior and by power characteristics. Transients under given control law are shown in fig. 10...fig. 12. According to tongue and rotor speed transients, it's evident that developed law provides the tongue equalling 0.1 of nominal one even when rotor speed equals 0.5 of nominal one. At that starting current (fig. 11) exceeds nominal value by 10 % only, so power loss during acceleration remains at level of loss during nominal mode (fig. 12).

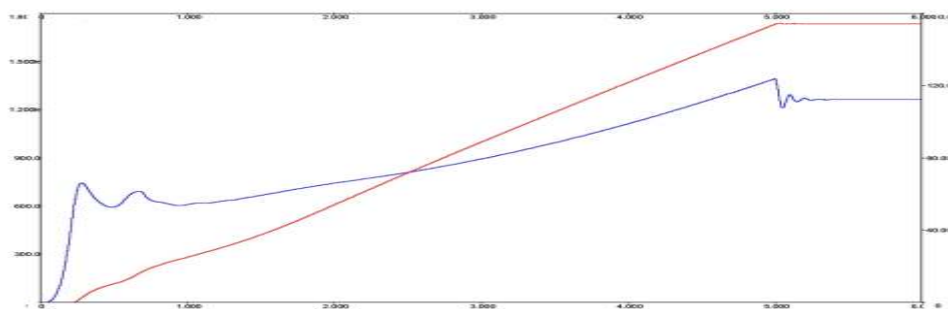


Fig. 10: The electromagnetic torque and rotor speed during adjustment from developed law

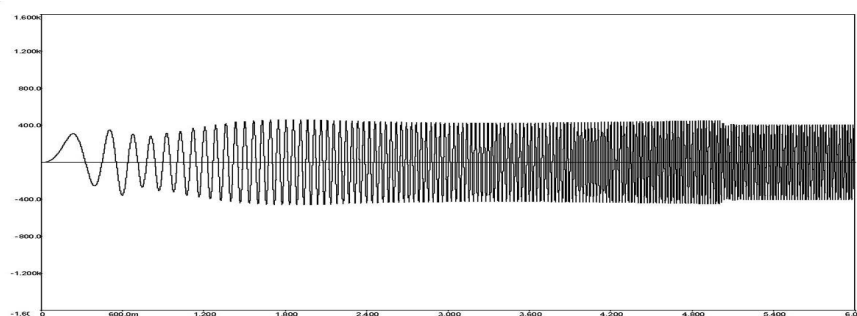


Fig. 11: The stator current during adjustment from developed law

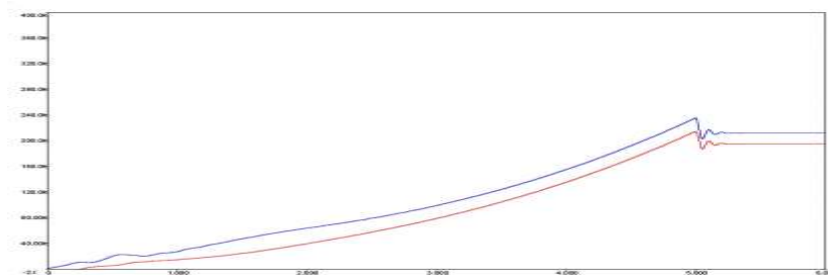


Fig. 12: The output power inverter and mechanical power induction motor

Simulation models have been proposed for the calculation of the induction motor dynamic characteristics. The accuracy of the designed method and comparison of the simulated results with the prototype data have been examined on the base of using of the developed models with predetermined parameters of induction motors.

The CASPOC models of PWM control

The developed control law is realized on PWM principle. CASPOC models of control system of the power inverter are designed. Its allowed realization of different ways of pulse-width modulation (phase and rectangular). In the CASPOC model of the phase PWM (fig. 13), turn-on time and turn-off time for each pulse of one period of modulation frequency are obtained.

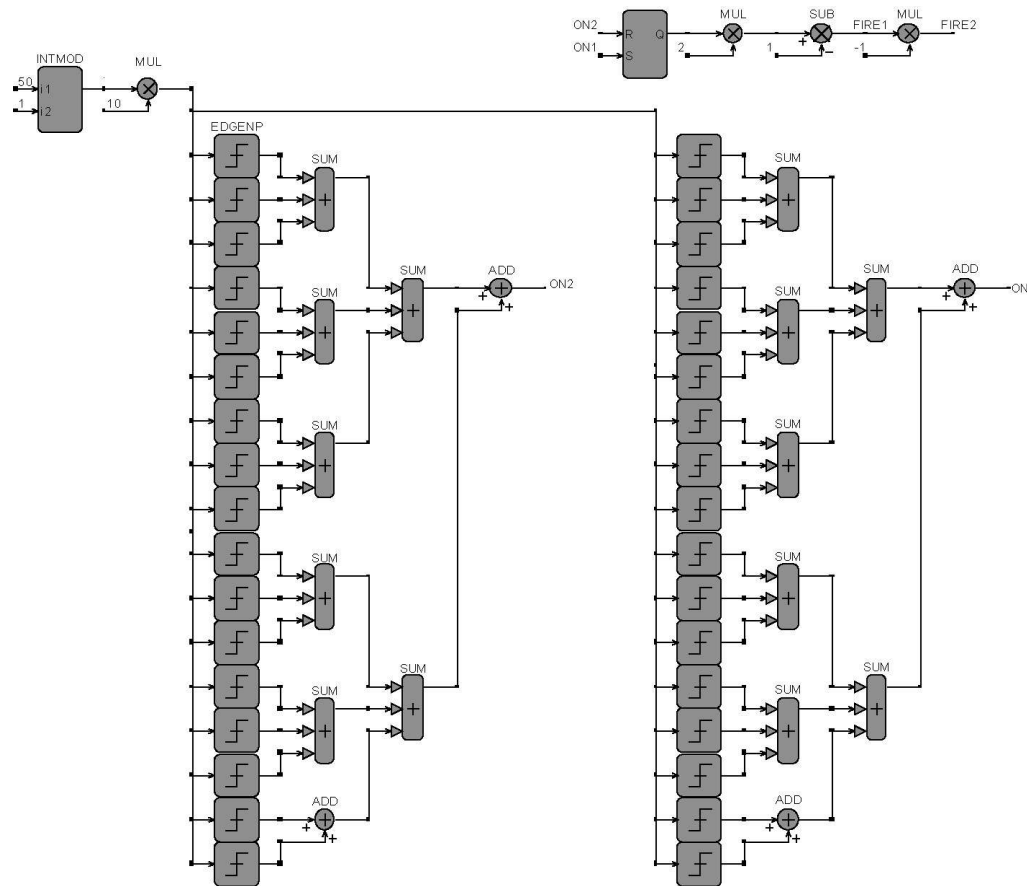


Fig. 13: The model of the phase PWM

In the CASPOC model of the rectangular PWM (fig. 14), there is rectangular voltage source with carrier frequency and sinusoidal source with modulation frequency, which controls pulse width. By varying amplitude of modulation sinusoid, it's possible to vary modulation depth.

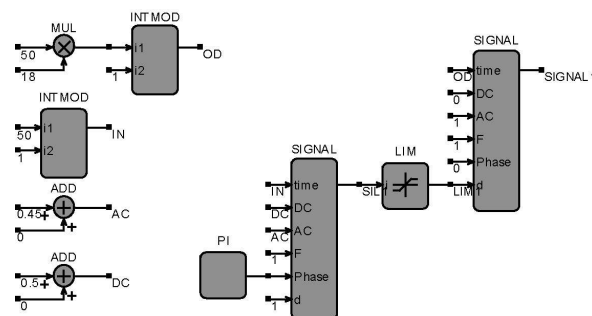


Fig.14. Block realizes rectangular PWM

The PWM control of three-phase power inverter on average voltage value at period provides adjustment of value and formation of quasi-sinusoidal curve of output voltage on average voltage value at period of carrier frequency during constant value of input voltage. At that given ratio of voltage and frequency is provided during over the whole of adjustment diapason. Scopes of output phase voltages of the power inverter and currents of stator winding of the induction motor are shown in fig. 15 and fig. 16 accordingly. It's shown in fig. 14, that stator currents differ from harmonic on integral characteristic (current integral at period of carrier frequency) no more than 3%.

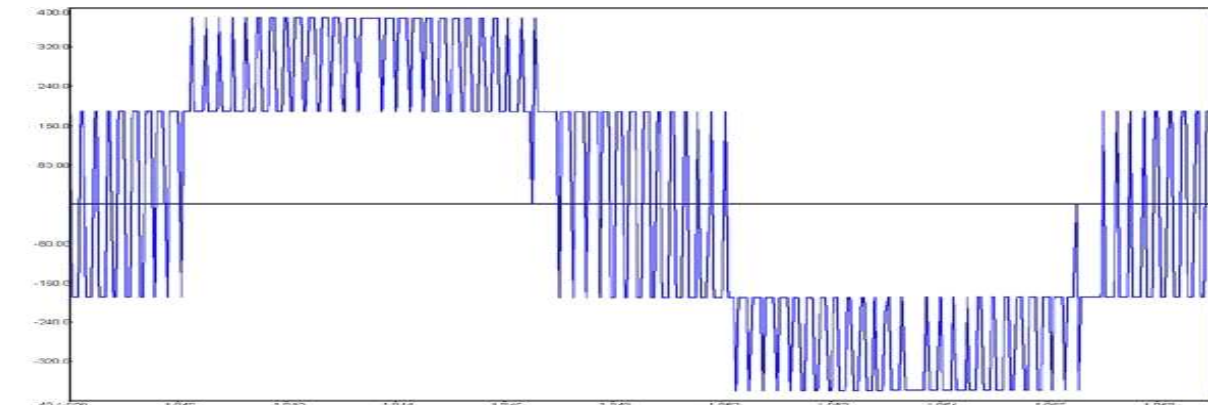


Fig. 15: The output phase voltage of thr power inverter

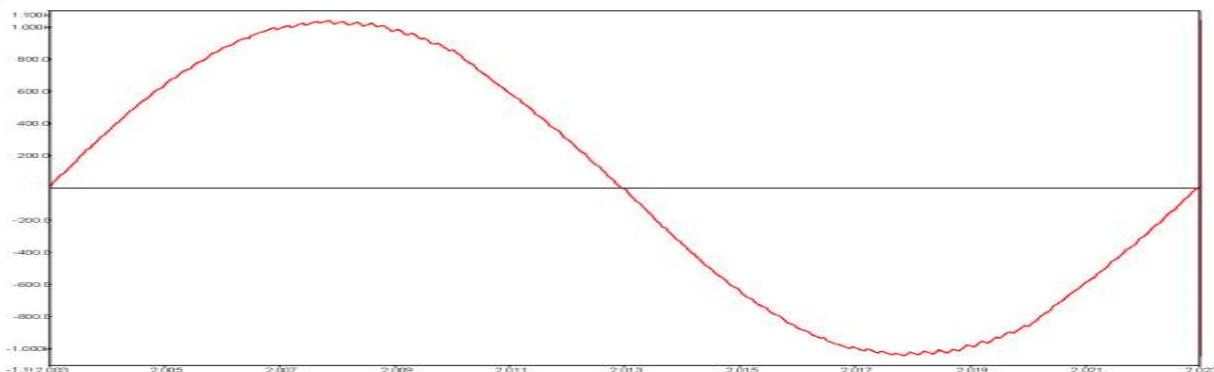


Fig. 14: The currents of stator winding of the induction motor

Conclusions

Transient and dynamic mode research is conducted with using of the proposed simulation CASPOC models of the considered traction induction drive. The obtained simulation results allows designing the control for the most important modes that enable to create a procedure, permitting to synthesize optimum control laws both by dynamic characteristics, and by power parameters.

It is shown, that selecting of the control law according to parameters of induction motor for traction application, mechanical load and operate mode allows increasing a motor start-up torque, reducing a start-up time, reducing ratio of start-up currents. By using the offered procedure, the control laws for start-up mode are designed. It improves drive characteristic, for example, developed law provides the tongue equaling 0.1 of nominal one even when rotor speed equals 0.5 of nominal one. At that starting current exceeds nominal value by 10 % only, so power loss during acceleration remains at level of loss during nominal mode.

At that the linear law of frequency and amplitude adjustment is examined as the initial variant. The initial conditions for frequency and amplitude are 10% of their nominal values. Such law turns out to be not effective enough, especially during high active load torque or dry friction torque (the load torque consists of active torque, viscous and dry friction torques). Though electromagnetic torque

increases smoothly (without rippling), but its average value is low as compared to total load torque and deficient to start the induction motor. The rotor moving starts late. More effective start-up can be provided, if the law with initial values of frequency and voltage equaling up to 25% of nominal values were used. But it increases the electromagnetic torque's rippling and causes currents' increase.

The influence of factors describing the frequency and voltage adjustment on the dynamic characteristics of electromagnetic torque and currents is researched. Limiting values of these factors for induction motor are discovered during different ratios of load torque's components. In some cases dynamic characteristic of electromagnetic torque has a collapse at the middle stage of acceleration during linear law of powering voltage frequency, so nonlinear control law should be used for more effective control.

The main simulation results of the dynamic behavior for traction induction drive are obtained and treated in the form of recommendations for future design.

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