Automatic Temperature Regulation System of Locomotive Traction Induction Motors With Power Losses Minimization

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Contribution to the state of the art

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Abstract: The air cooling systems are shown to be used to provide required temperature condition of traction induction motors on locomotives. The automatic temperature regulation system is developed for its using to solve such a task. Results of experimental investigation showed that the AO63-4 induction motor stator end winding on the side opposite to air supply is the most heated part of the induction motor. Based on the results of the research, it was used an aperiodic second-order transfer function for approximation of the thermal transient curves. The design of an induction motor control system maintaining operating mode with minimum of the stator current are considered. It is shown that the modes of minimum of the stator current and minimum of power losses are quite close to each other. The MatLab simulation results taking typical nonlinearities and iron power losses in an induction motor and conduction and commutation power losses in semiconductors of frequency converter into account are presented. It is shown that as a result of application of the suggested system the power losses reduction may be led up to 20 % relatively to classical scalar control.

Key words: induction motor, locomotive, automatic system, equivalent circuit, power losses minimization.

Introduction

Application of induction motors as traction and auxiliary means of rolling stock has become popular due to their relative simplicity, high reliability, efficiency, satisfactory design, compactness and performance characteristics. However, the induction motor quality indicators for rated operating conditions do not coincide with those of real operation in response to the variety of factors.

Analyzing the results of researches [6] one can conclude that many failures and malfunctions are directly or indirectly related to or caused by extensive heating of the different motor parts involved in machine operation. That is why the accurate track of motor thermal state and adequate response of the motor control system to abnormal situations are very important.

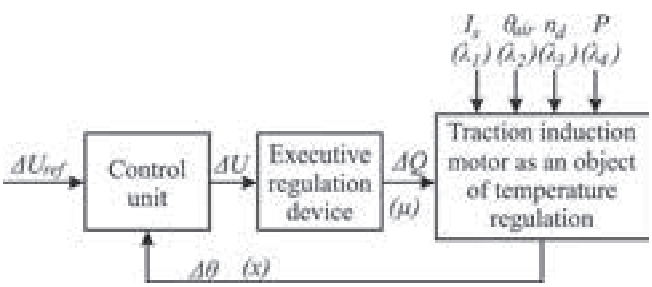
Except causing failures and damages, the temperature of induction motor windings is known to affect the operating modes of the electric drive, particularly static mechanical characteristics and it also violates the settings of optimal control systems on any quality indicator [4]. This is particularly critical in traction electric drives, where except meeting strict requirements on the energy and mass and dimensions, the drive must provide a prescribed driving force to ensure the required quality of the transition process.

It follows from the survey carried out that for implementation of traction forces of the electric drive with power losses minimization it is necessary to consider fully a temperature condition of the traction induction motor and take measures to prevent it from extreme or often overheating.

To provide the required temperature condition of traction motors on locomotives air cooling systems are used. In [7], in particular, it is noted that cooling regulation of traction electric motors allows reducing the cooling air flow through the drive motor by 25% when outdoor temperature is below 18 °C. The greatest effect in solving the problem of increasing efficiency of cooling systems can be achieved if cooling systems of traction motors will be equipped with a controlled drive fans, allowing continuous and automatic change of cooling air flow depending on the temperature of the heated parts of the equipment, its current load and temperature of cooling air.

Automatic temperature regulation system of locomotive traction induction motors

The static and dynamic characteristics of object of regulation, the executive regulation device and the control unit which can be implemented in various mathematical models have to be known for creation of automatic regulation system. The scheme of automatic temperature regulation system of traction induction motors, feasible for using on a locomotives, is given in Fig. 1.



μ - regulatory reference, x – regulated parameter, λ_i – disturbances; $\Delta\vartheta$ – change of temperature of a traction induction motor, ΔU_{ref} – change of reference, ω – change of speed of fan shaft, ΔQ – change of the air flow, I_s – stator current of a traction induction motor, ϑ_{air} – temperature of the air, n_d – frequency of rotation of the diesel-generator, P – power of the diesel-generator

Figure 1. Scheme of automatic temperature regulation system

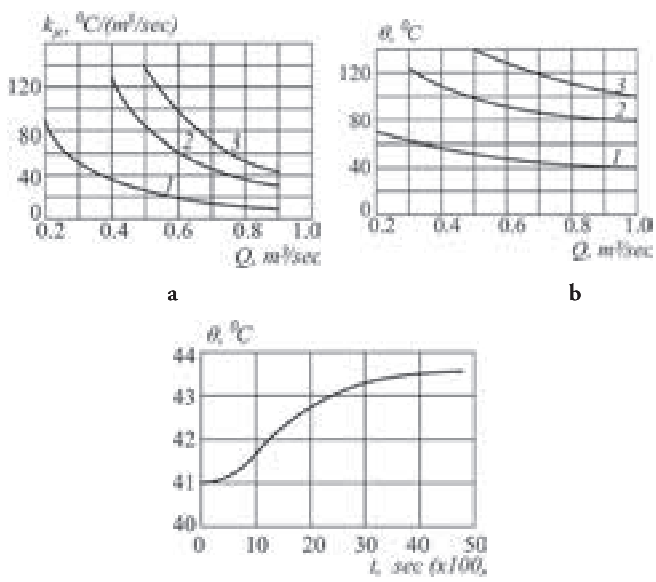
It is necessary to analyse properties of each of functional units of scheme (Fig. 1) for designing up the whole block diagram of automatic temperature regulation system. In this investigation the authors considered the possibility of implementation of automatic system using the centrifugal fan driven by induction motor drive with frequency converter as the executive regulation device.

Traction induction motor as an object of temperature regulation

As a result of experimental research [11] it was found that the greatest overheating occurred in the stator end winding on the side opposite the air supply. In this regard, the stator end winding was chosen as the element limiting in heating of the AO63-4. Hereafter, the experimental results related to the stator end winding are discussed.

Results of experimental research of static and transient modes are shown in Fig. 2. The ambient temperature is 18…25 °C.

As it can be seen from Fig. 2, the experimental curves of the stator winding temperature and static characteristics of the cooling system θ(Q) are non-linear in the whole range of the cooling air flow, that indicates significant non-linearity of the induction motor as an object of regulation of temperature. The values of the transfer coefficients k_μ vary within wide limits (10 times or more) depending on Q and I_s. k_μ increases with increasing of the I_s stator current. The smaller values of Q correspond to higher values of k_μ.



1 – I_{s*} = 0,5, 2 – I_{s*} = 0.8, 3 – I_{s*}= 1.0, $I_{s*} = I_s / I_{s\ rat}$

Figure 2. Experimental results of transfer coefficient depending on the air flow (a), temperature of the stator end winding depending on the air flow (b) and on the time (c)

It is shown in [7] that the design of the automatic regulation system needs just determination of the dynamic characteristics and parameters of the cooling system of the traction electric motors only on the regulatory reference with all possible changes of disturbances. For the design of regulation system it requires an experimental curves presented in the form of mathematical functions, written as a transfer functions.

Based on the results of the research, for approximating the thermal transient it was decided to use the following type of transfer function:

$$W(p) = \frac{k_\mu}{(T_1 p + 1)(T_2 p + 1)}, \qquad (1)$$

where k_μ determined by Fig. 2,a, T_1, T_2 denote the time constants.

To determine time constants Oldenberg and Sartorius methods and Orman interpolation method have been used. Parameter values of the transfer functions (1) are summarized in Table 1.

Table 1. Parameters of transfer function (1)

Baseline	T_1, sec	T_2, sec	k_μ, °C/(m3/sec)
Q = 0,91 m³/sec, $I_* = 1$, $u_{s*} = 1$, $f_{s*} = 1$	958	169	42
Q = 0,91 m³/sec, $I_* = 0.5$, $u_{s*} = 1$, $f_{s*} = 1$	821	152	12
Q = 0,51 m³/sec, $I_* = 1$ $u_{s*} = 1$, $f_{s*} = 1$	969	271	130
Q = 0,51 m³/sec, $I_* = 0.5$, $u_{s*} = 1$, $f_{s*} = 1$	659	101	25
Q = 0,51 m³/sec, $I_* = 0.5$, $u_{s*} = 0.23$, $f_{s*} = 0.35$	659	101	25
Q = 0,51 m³/sec, $I_* = 1$, $u_{s*} = 0.23$, $f_{s*} = 0.35$	969	271	130

Here subscript * denotes the relative value of some parameter, i.e. $u_{s*} = u_s / u_{s\,rat}$, $f_{s*} = f_s / f_{s\,rat}$, where u_s denotes the stator voltage, f_s denotes frequency of the stator current, subscript rat denotes the rated value of some parameter

Analysis of the results comparison of the transients curves obtained during the experiment with the curves obtained in the simulation of the transfer function (1) (parameters of transfer function defined in Table 1) showed high results convergence.

Centrifugal fan as an executive device of automatic temperature regulation system

The important condition for correct design of system control of cooling fan electric drive is precise identification of fan parameters as a mechanical load for electric motor. The main parameter of fan, in terms of electric drive, is relation between T_L load torque and the ω rotor speed: $T_L = f(\omega)$ called a mechanical characteristic. The kind of this function as well a relation between the T motor torque and the rotor speed determine the initial energy efficiency of electric drive.

The mechanical characteristic of the fan can be written as follow:

$$T_L = T_{L0} + \frac{C_H H_s + \omega^2}{\omega \eta(\omega, H_s)} \sqrt{\omega^2 - \frac{H_s}{H_0}}, \qquad (2)$$

where T_{L0} is an idling load, H_0 is a static air pressure, H_s is an air pressure under closed latch, i.e. air flow $Q = 0$, C_H is a empirical coefficient, $\eta(\omega, H_s)$ is a fan efficiency.

Relation between the H air pressure and the ω rotor speed can be described as follow:

$$H = H_0 \left(\frac{\omega}{\omega_{rat}}\right)^2 - cQ^2, \qquad (3)$$

where c is an empirical coefficient.

Equations (2), (3) contain the main parameters of fan, including efficiency change, and allow to take it into account in the further researches as a load torque for induction motor.

Induction motor drive as a regulation device of automatic temperature regulation system

The correct mathematical model of the induction motor taking all possible losses, and also nonlinearity caused by features of work in various modes into account is necessary for synthesis of control system of electric drive of automatic temperature regulation system. It is obvious that the greatest difficulties are presented by the accounting of losses in iron [1, 10]. The equivalent circuit for induction motor with stator and rotor iron losses is shown in Fig. 3.

In Fig. 3 and further in the article R_s, R_r denote the stator and the rotor resistances; R_μ denotes the resistance equivalent to iron losses caused by eddy current and hysteresis; $L_{\sigma s}$, $L_{\sigma r}$, L_{μ} denote the stator and rotor leakage inductances and magnetizing inductance, respectively; ω_k denotes the electrical angular frequency (or speed) of reference frame; u_s, i_s, i_r, i_μ, i_i denote the voltage and currents in a corresponding branches of the circuit.

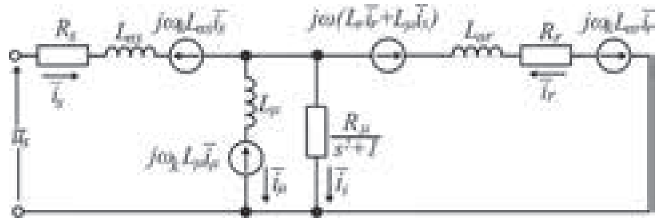


Figure 3. Equivalent circuit for induction motor

A problem with the loss model is the complexity caused by additional contour formed by iron losses and magnetizing branches.. A good way to simplify the mathematical model is based on the fact that the magnetizing current i_μ is much larger than the iron loss current i_i.

$$|\bar{\imath}_\mu| \gg |\bar{\imath}_i|. \quad (4)$$

Then it follows from c ircuit (Fig. 3) that i_μ is approximated so that:

$$\bar{\imath}_\mu \cong \bar{\imath}_s + \bar{\imath}_r. \quad (5)$$

The stator and rotor voltage equations in the synchronous frame written with taking (5) into account for circuit (Fig. 3):

$$\bar{u}_s = R_s\bar{\imath}_s + L_{\sigma s}\frac{d\bar{\imath}_s}{dt} + j\omega_k L_{\sigma s}\bar{\imath}_s + L_\mu\frac{d(\bar{\imath}_s+\bar{\imath}_r)}{dt} + jL_\mu\omega_k(\bar{\imath}_s+\bar{\imath}_r), \quad (6)$$

$$0 = R_r\bar{\imath}_r + L_{\sigma r}\frac{d\bar{\imath}_r}{dt} - j\omega\left(L_r\bar{\imath}_r + L_\mu\bar{\imath}_s\right) + j\omega_k L_{\sigma r}\bar{\imath}_r + L_\mu\frac{d(\bar{\imath}_s+\bar{\imath}_r)}{dt} + jL_\mu\omega_k(\bar{\imath}_s+\bar{\imath}_r), \quad (7)$$

$$\bar{\imath}_s + \bar{\imath}_r = \frac{s^2+1}{R_c}\left(L_\mu\frac{d(\bar{\imath}_s+\bar{\imath}_r)}{dt} + jL_\mu\omega_k(\bar{\imath}_s+\bar{\imath}_r)\right) + \bar{\imath}_\mu. \quad (8)$$

The electromagnetic torque of the induction motor is given by:

$$T = \frac{3p_n}{2L_{\sigma r}}\left[\left(L_{\sigma r}i_{ru} + L_\mu i_{\mu u}\right)L_\mu i_{\mu v} + \left(L_{\sigma r}i_{rv} + L_\mu i_{\mu v}\right)L_\mu i_{\mu u}\right]. \quad (9)$$

The mechanical move is described by:

$$T - T_L = J\frac{d\omega}{dt}. \quad (10)$$

The effect of saturation on main magnetic path is taken into account by:

$$L_{\mu*} = -0{,}002I_{\mu*}^6 + 0{,}037I_{\mu*}^5 - 0{,}261I_{\mu*}^4 + 0{,}87I_{\mu*}^3 - 1{,}278I_{\mu*}^2 + 0{,}214I_{\mu*} + 1{,}413. \quad (11)$$

The nonlinear function linking the resistance equivalent to the iron losses and frequency is presented by:

$$R_\mu = \begin{cases} 88{,}3135 + 5{,}646f_s + 0{,}0534f_s^2, & f_s \le 50Hz, \\ 1261{,}3 - \dfrac{37868}{f_s}, & f_s > 50Hz. \end{cases} \quad (12)$$

For evaluating of efficiency the next expressions are used.

Mechanical power on the motor shaft:

$$P_{mech} = T\omega. \quad (18)$$

Active electric power:

$$P_s = \frac{3}{2}(i_{su}u_{su} + i_{sv}u_{sv}). \quad (19)$$

Reactive electric power:

$$Q_s = \frac{3}{2}(i_{sv}u_{su} - i_{su}u_{sv}). \quad (20)$$

The copper power losses in the stator winding:

$$\Delta P_{sc} = \frac{3}{2} I_s^2 R_s = \frac{3}{2} (i_{su}^2 + i_{sv}^2) R_s. \qquad (21)$$

The copper power losses in the rotor winding:

$$\Delta P_{rc} = \frac{3}{2} I_r^2 R_r = \frac{3}{2} (i_{ru}^2 + i_{rv}^2) R_r. \qquad (22)$$

The iron power losses in the stator and rotor core:

$$\Delta P_i = \frac{3}{2} \frac{u_{12}^2}{R_\mu}, \qquad (23)$$

where u_{12} voltage can be taken according to Fig. 3:

$$\bar{u}_{12} = L_\mu \frac{d(\bar{\imath}_s + \bar{\imath}_r)}{dt} + jL_\mu \omega_k (\bar{\imath}_s + \bar{\imath}_r). \qquad (24)$$

The module of u_{12} voltage in the steady state can be written as follow:

$$u_{12} = u_{12u}^2 + u_{12v}^2 = \left(\omega_k L_\mu (i_{su} + i_{ru})\right)^2 + \left(\omega_k L_\mu (i_{sv} + i_{rv})\right)^2. \qquad (25)$$

The power balance may be written as follow:

$$P_s = \Delta P_{sc} + \Delta P_{rc} + \Delta P_i + P_{mech}. \qquad (26)$$

Control system of induction motor drive

The most common features of electric drives of cooling fans for locomotives traction electric equipments and motors are highlighted from the survey of operation modes of the auxuliary drives and machines. It can be listed as follows:

- shifting of speed to its lower values causes considerable reducing of load torque and mechanical power on the motor shaft;
- the long period of time of operation mode with permanent speed and load torque;
- the absence of reverse mode;
- the restricted range of speed change;
- the absence of overloads, the value of overload may be determined in advance;
- the start-up time is not limited, the start is prefered to have a small start-up time for restricting dinamic overloads.

For all these reasons, the strict requires in transient modes to closed-loop system control of cooling fan electric drive are not applied. For restricting the dinamic overloads it is wisely to put not a steplike reference signal but a ramped one.

It is obvious that the scalar control system thoroughly satisfies all features mentioned above. The scalar control system of induction motor are shown in Fig. 4.

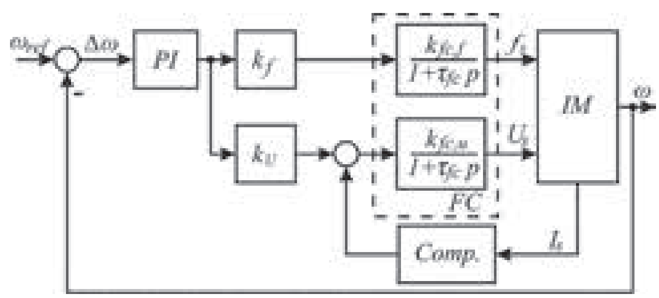


Figure 4. The scalar control system of induction motor

The voltage source inverter of frequency converter is presented as the next transfer functions of frequency and voltage:

$$W_f(p) = \frac{k_{fc,f}}{1 + \tau_{fc} p}, \qquad (27)$$

$$W_u(p) = \frac{k_{fc,u}}{1 + \tau_{fc} p}, \qquad (28)$$

where k_{fc} is the gain and τ_{fc} is the time constant.

k_f and k_u coefficients provide the proportional relationship between f_s frequency of stator current and U_s stator voltage.

The equation of the speed PI-controller:

$$W_{sp}(p) = k_{sp} + \frac{1}{\tau_{sp} p}, \quad (29)$$

where k_{sp} is the gain and τ_{sp} is the time constant.

The unit in Fig. 4 named *Comp* takes a function of compensation of voltage drop over the stator resistance. Two cases of such compensation are applied: *IR*-compensation and *IZ*-compensation.

Expression for voltage augment in case of *IR*-compensation:

$$U_{aug} = U_{s,rat} f_{s*} + I_{s,rat} R_s (1 - f_{s*}). \quad (30)$$

Expression for voltage augment in case of *IZ*-compensation:

$$U_{aug} = U_{s,rat} f_{s*} + I_{s,rat} \sqrt{R_s^2 + X_s^2} (1 - f_{s*}). \quad (31)$$

Controller of temperature as a control unit

Controller of temperature working on a signal of mismatch of the reference and feedback is used as a control unit of automatic temperature regulation system. The type and parameters of the controller influence on a steady state and transient mode. It needs to find a correct point where transient time, error of regulation, variability, etc. have a satisfying values. In this work P- and PI-controller of temperature are presented and discussed:

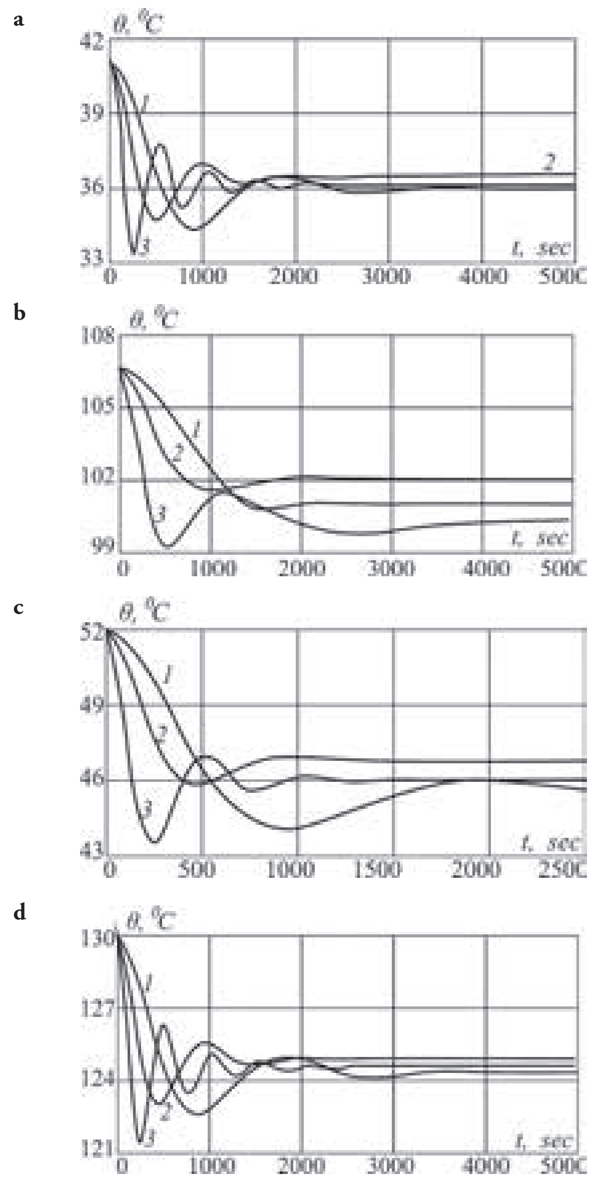
$$W_{CU}(p) = k_{CU}, \quad (32)$$

$$W_{CU}(p) = k_{CU} + \frac{1}{\tau_{CU} p}. \quad (33)$$

Simulation of automatic temperature regulation system

Simulation of automatic temperature regulation system was carried out by using of Matlab Simulink. The object of temperature regulation was simulated by transfer function (1) with parameters presented in Table 1. The centrifugal fan was described by (2), (3). The induction motor was presented in accordance to (6) – (10), the nonlinearity are implemented by (11) – (17). The energy equations of an induction motor are included by (18) – (26). The scalar control system was implemented by (27) – (31). The equations of (32), (33) were used to simulate the control unit in various configurations of automatic temperature regulation system.

The results of simulation of transient modes of automatic temperature regulation system are shown in Fig. 5.



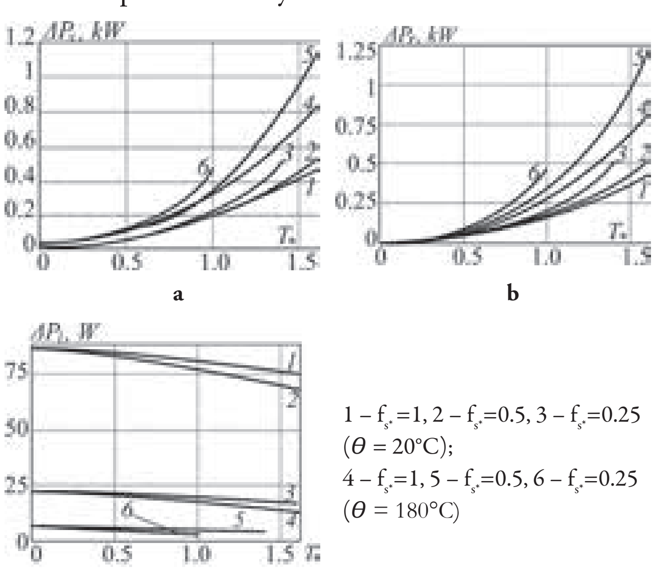
1 – $W_{CU}(p) = 3$, 2 – $W_{CU}(p) = 10$, 3 – $W_{CU}(p) = (p+0.0008)/p$.
a – $I_{s*} = 1.0$, $Q = 0.91$ m^3/sec, $u_{s*} = 1$, $f_{s*} = 1$,
b – $I_{s*} = 0.5$, $Q = 0.91$ m^3/sec, $u_{s*} = 1$, $f_{s*} = 1$,
c – $I_{s*} = 1.0$, $Q = 0.51$ m^3/sec, $u_{s*} = 0.23$, $f_{s*} = 0.35$,
d – $I_{s*} = 0.5$, $Q = 0.51$ m^3/sec, $u_{s*} = 0.23$, $f_{s*} = 0.35$

Figure 5. The temperature change of the stator winding of the traction induction motor

The analysis of results of simulation let us make some conclusions. The value of transient time changes over a wide range depending on the cooling air flow and the stator current. The value of transient time decreases as the value of stator current increase. At the same time, the value of transient time increases while the value of the air flow increase too.

The increase of value of controller gain is an effective way to reduce error of regulation but it leads to decreasing of stocks of stability and deteriorating of quality indicators. It includes the increase of variability, overshooting and transient time. More expedient way in relation to increasing in value of controller gain is implementation of PI-controller. It leads not to the increase of variability and transient time but to eliminating of error of regulation in steady state.

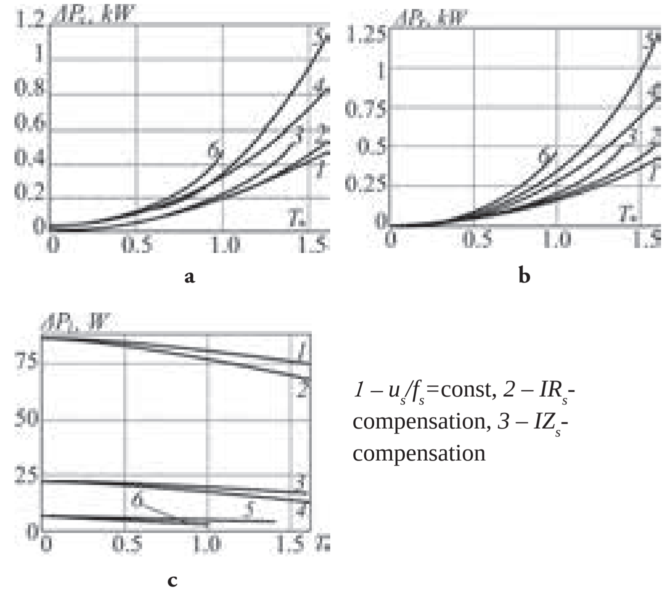
The gain and time constant of PI-controller is expedient to change at any change of regulation values and reference for providing constant stocks of stability of system and rational values of quality indicators. It can be explained by Table 1 and equations (1) – (26) and peculiarity of the scalar control system as the static and dynamic parameters of transfer functions of regulation system are variables. It is possible to implement it in systems with microprocessor automatic controllers due to continuous change of values of parameters by software.



1 – f_{s*}=1, 2 – f_{s*}=0.5, 3 – f_{s*}=0.25 (θ = 20°C);
4 – f_{s*}=1, 5 – f_{s*}=0.5, 6 – f_{s*}=0.25 (θ = 180°C)

Figure 6. Power losses in copper of the stator (a), copper of the rotor (b) and iron of the core (c) depending on the relative torque under the scalar control with u_s/f_s=*const*

The results of simulation of energy processes in 4A112M6U3 induction motor are shown in Fig. 6 and 7.



1 – u_s/f_s=const, *2* – IR_s-compensation, *3* – IZ_s-compensation

Figure 7. Power losses in copper of the stator (a), copper of the rotor (b) and iron of the core (c) depending on the relative torque under θ = 20°C and f_{s*}=0.25

The analysis of results of simulation shows that there is quite narrow range of change of the torques for each of the applied scalar control system where this scalar control system is appeared to be more energysaving than the others. It speaks about need of creation of the high-dynamic control systems allowing to minimize power losses in the wide range of change of the torque and speed.

Induction motor drive with power losses minimization

Survey of efficiency optimization techniques

Optimum design of induction motor is a nonlinear multi-dimension problem whereas optimal control is a single or two dimension problems. Numerous scientific papers on the problem of loss reduction in induction motor drive have been published in the last few decades. Although good results have been achieved, there is still no generally accepted technique for loss minimization. According to the proceedings and results of scientific researches, there are three main techniques for dealing with the problem of efficiency optimization of the induction motor drive [4,12]:

- simple state control;
- loss model control;
- search control.

The simple state control is based on the control of one of the variables in the drive [2]. This variable must be measured or estimated and its value is used in the feedback control of the drive, with the aim of running the motor by predefined reference. This technique is simple, but gives good results only for a narrow set of operation conditions. Also, it is sensitive to parameter changes in the drive due to temperature changes and magnetic circuit saturation.

The loss model control are fast because the optimal control is calculated directly from the loss model [13]. The main disadvantage of this technique is that the power loss simulation and calculation of the optimal operating conditions is very complex and it is also highly sensitive to parameter variations in the drive.

The search control uses the on-line procedure for efficiency optimization [8]. The on-line efficiency optimization control on the basis of search changes one of variables in steps until the measured input power settles down to the lowest value is very attractive. Search technique has an important advantage compared to other techniques. It is absolutely insensitive to parameter changes while effects of the parameter variations caused by temperature and saturation are very expressed in two other techniques. Also there is an significant drawback in its use: convergence of controlled variable to its optimal value sometimes can be too slow, and it never reaches the value of minimal losses then in small steps oscillates around it.

There are some hybrid techniques that combine peculiarities and advantages of three techniques mentioned above [1, 9, 5], but, nevertheless, it can be classified by presented ones.

As a result of survey carried out and features of electric drives of cooling fans, it has been concluded that the search control with indirect power losses minimization is worth to be applied. The variable controlled to reach the optimization point is the stator voltage, the variable choosen to be minimized is the stator current. The next subsections is presented to prove proximity of minimum current and minimum losses modes.

Overall power losses model of induction motor drive

Besides the induction motor taken part in energy conversion, it is also voltage source inverter of frequency converter takes its place in electrical energy conversion. As a rule of thumb, it used to be eliminated from considering as a source of power losses due to a values of losses slightly compared to values of induction motor one. But now, since the computer technology made a huge step forward, it is not so onerous and tremendous to extract the equations of power losses in frequency converter.

The average power losses of frequency converter over switching period of time are determined by follow equations [9]:

- for transistor and diode conduction losses:

$$\Delta P_{c,VT} = \frac{1}{2\pi}\int_0^{\pi} u_{ce}(i_s,\theta_j) I_s \sin(2\pi f_s t)\frac{1+\mu(t)}{2}\, d(2\pi f_s t), \quad (34)$$

$$\Delta P_{c,VD} = \frac{1}{2\pi}\int_{\pi}^{2\pi} u_{ce}(i_s,\theta_j)\, |I_s \sin(2\pi f_s t)|\, \frac{1+\mu(t)}{2}\, d(2\pi f_s t), \quad (35)$$

- for transistor turn-on and turn-off commutation losses:

$$\Delta P_{sw,VT} = \frac{1}{2\pi}\int_0^{\pi} \left(E_{on}(i_s) + E_{off}(i_s)\right)\frac{U_{dc}}{U_{dc,rat}}\frac{1}{\tau}\, d(2\pi f_s t), \quad (36)$$

- for diode commutation losses due to reverse recovery:

$$\Delta P_{rr,VD} = \frac{1}{2\pi}\int_0^{2\pi} E_{rr}(i_s)\frac{U_{dc}}{U_{dc,rat}}\frac{1}{\tau}\, d(2\pi f_s t). \quad (37)$$

In (34) – (37) u_{ce} denotes the voltage drop over collector-emitter, E_{on} and E_{off} denote the transistor turn-on and turn-off energy, E_{rr} denotes the diode energy reverse recovery. *μ(t)* denotes the modulation index.

The modulation index *μ(t)* is determined by type of used modulation. In case of sinusoidal pulse width modulation the modulation index is a function of sinus, in case of space vector pulse width modulation the modulation index can be evaluated as follow [3]:

In (34) – (37) u_{ce} denotes the voltage drop over collector-emitter, E_{on} and E_{off} denote the transistor turn-on and turn-off energy, E_{rr} denotes the diode energy reverse recovery. *μ(t)* denotes the modulation index. The modulation index *μ(t)* is determined by type of used modulation. In case of sinusoidal pulse width modulation the modulation index is a function of sinus, in case of space vector pulse width modulation the modulation index can be evaluated as follow [3]:

$$\mu(t) = \mu_0 sin(2\pi f_s t) + \frac{3\sqrt{3}}{8\pi}\sum_{k=0}^{\infty}\left(\frac{\sin(3(4k+1)2\pi f_s t)}{18k^2 - 9k + 1} - \frac{\sin(3(4k+1)2\pi f_s t)}{18k^2 + 27k + 10}\right), \quad (38)$$

where $k = 0,1,2,\ldots$

The dependence of voltage drop over collector-emitter from current and temperature of junction can be written as follow:

$$u_{ce}(i_s, \theta_j) = 1{,}21 + 9{,}93 \cdot 10^{-3} i_s - 1{,}88 \cdot 10^{-3}\theta_j - 2{,}54 \cdot 10^{-5} i_s^2 + 3.22 \cdot 10^{-5} i_s \theta_j. \quad (39)$$

To simplify (34) – (37) it has to substitute losses over switching period of time by real-time losses calculation per component:

$$\Delta P_{c,VT} = u_{ce}(i_s, \theta_j) i_s \frac{\tau_{cond}}{\tau}, \quad (40)$$

$$\Delta P_{c,VD} = u_{ce}(i_s, \theta_j) i_s \frac{\tau_{cond}}{\tau}, \quad (41)$$

$$\Delta P_{sw,VT} = \left(E_{on}(i_s) + E_{off}(i_s)\right)\frac{U_{dc}}{U_{dc,rat}}\frac{1}{\tau}, \quad (42)$$

$$\Delta P_{rr,VD} = E_{rr}(i_s)\frac{U_{dc}}{U_{dc,rat}}\frac{1}{\tau}, \quad (43)$$

where τ denotes the switching period of time, τ_{cond} denotes time of conduction for this semiconductor. The overall power losses of frequency converter:

$$\Delta P_{fc} = 6\left(\Delta P_{c,VT} + \Delta P_{c,VD} + \Delta P_{sw,VT} + \Delta P_{rec,VD}\right). \quad (44)$$

The overall power losses of electric drive taken (17) – (26) and (40) – (44) into account has to be written as follow:

$$\Delta P_{ed} = \Delta P_s + \Delta P_c + \Delta P_r + \Delta P_{fc}. \quad (45)$$

Comparison between minimum current and minimum losses modes

As it was undermined in subsection 2.3 the scalar control system has been chosen to utilize. To provide the minimum power losses it needs to implement a gauge of active power or calculate by mathematical model. But for locomotives the mounting of complementary equipment is not such a widely used technique because of the strict limit of free space, sophistication in exploitation and maintenance. To implement the stator current sensor is much better way for reaching the aim. It leads to shift from point of minimum power losses inevitably and this shift has to be evaluated. It is obvious that analytical solving this problem is very complex task. The numerical methods has been utilized to get the relationship between power losses under the different modes. Mathematically, this task for the scalar control system can be written as follow:

$$\Delta P_{ed}(T, \omega, s) \rightarrow min \Rightarrow s_{opt,} \qquad (46)$$

where $s = \omega_0 - \omega$, s_{opt} denotes its optimal value in terms of losses minimization.

Table 2 contains the most important results of the numerical investigation for 4A112M6U3 induction motor. IGBT module of SKiiP 11HEB066V1 was used as a voltage source inverter.

The quantity comparison of overall power losses in electric drive between minimum current and minimum losses modes shows its almost thoroughly coincidence. So, the maximum mismatch in overall power losses under two considered modes for $0.2 \leq T_* \leq 1.5$ and $0.25 \leq \omega_* \leq 1.25$ equals to 8%.

Table 2. Comparison between minimum current and minimum losses modes

mode	ω*	ΔP$_{ed}$, W					
		T*=0.2	T*=0.4	T*=0.6	T*=0.8	T*=1.0	T*=1.2
minimum power losses	1.25	138.1	243.1	361.6	499.3	653.4	839.5
	1	116.3	212.3	324.9	458.3	615	793.5
	0.75	96.1	184.2	292.1	422.7	576.5	753
	0.5	77.2	159.2	263.5	491.5	543.2	718
	0.25	61.9	138.5	239.8	365.7	515.5	689.5
minimum current	1.25	146.2	246.3	362.3	499.1	659.5	841
	1	120.1	213.2	324.4	459	616	796.5
	0.75	97.3	184.2	292.3	423.8	579	777.5
	0.5	77.8	159.5	264.5	393.7	597	724
	0.25	62.1	139.4	241.8	369.1	521	691.2

Implementation of power losses minimization

The developed control system of induction motor are shown in Fig. 8, a. The control system may be divided into two subsystems: the common scalar control system having closed loop with speed feedback (Fig. 4) and the control system providing the minimum current mode.

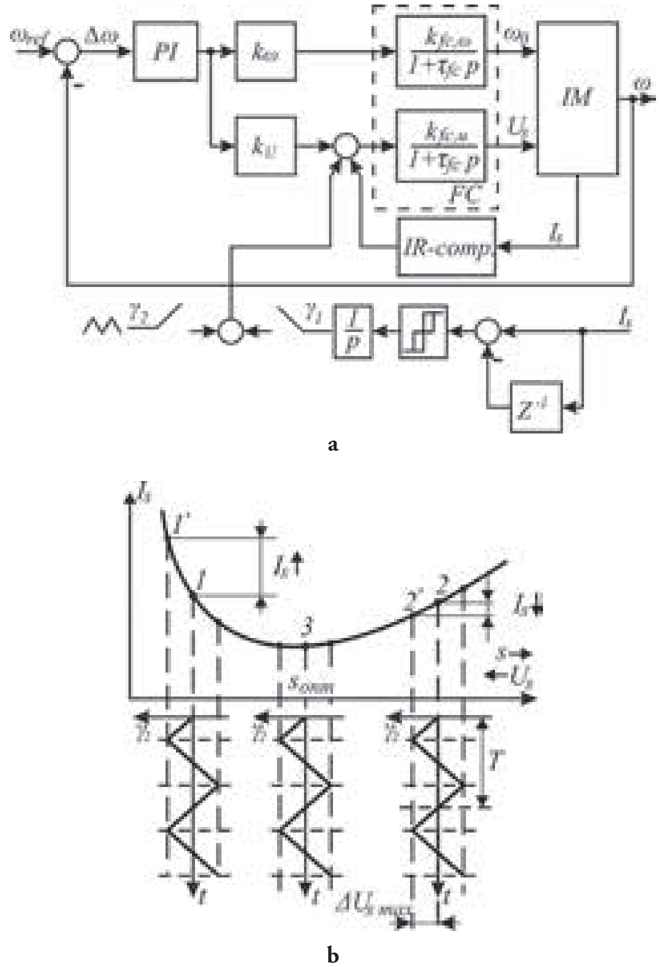


Figure 8. The scalar control system of induction motor with power losses minimization (a) and technique of searching for minimum of the stator current (b)

The essence of the control system providing the minimum current mode is the next. If a steady state of the operation can be found, the search control system is enabled, until the stator current reaches the minimum. It is used an external, periodical test signal, triangular shape wave, that determines the increases or the decreases of the additional voltage control signal. Once the minimum point was reached, the system operates in this new steady state, until a change in the stator current is detected.

The search technique uses as manipulated variable the γ_1 voltage and as test signal the γ_2 triangular voltage in order to change the stator voltage:

$$U_{s,tot} = U_s + \gamma_1 + \gamma_2. \qquad (47)$$

It is applied that the γ_2 test signal has the amplitude $\Delta U_{s,max}$ and the τ_γ period then the position of the current operating point (1, 2 or 3 in Fig. 8, b) relative to the minimum point can be determined by the variation of the ΔI_s stator current due to the $+\Delta U_{s,max}$ test signal in the first $\tau_\gamma /2$ half of period so that:

- if $\Delta I_s > 0$ then the slip is $s < s_{opt}$ (point 1);
- if $\Delta I_s < 0$ then the slip is $s > s_{opt}$ (point 2);
- if $\Delta I_s = 0$ then the slip is $s = s_{opt}$ (point 3).

In order to make the induction motor to operate close to minimum point it needs to choose the ramp sign of the manipulated variable ($\gamma_1 = \varepsilon t$, where ε is an empirical coefficient) so that:

- if ΔI_s increases then γ_1 has to decrease the stator voltage:

$$\Delta U_s = -\gamma_1 + \gamma_2 = -\varepsilon t + \gamma_2 = \gamma; \tag{48}$$

- if ΔI_s decreases then γ_1 has to increase the stator voltage:

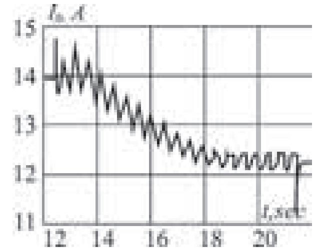
$$\Delta U_s = \gamma_1 + \gamma_2 = \varepsilon t + \gamma_2 = \gamma; \tag{49}$$

- if $\Delta I_s \approx 0$ then the signal is $\gamma \approx 0$.

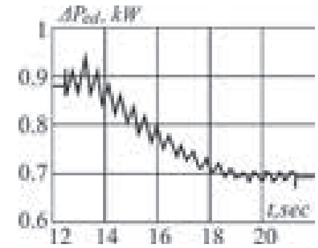
Simulation of induction motor drive

Simulation of the drive was carried out in MatLab as follows. At the first interval of time the soft start of the induction motor to the referenced speed was carried out. The system of the stator current minimization is disconnected. After completion of transition processes the search control technique is added to classical system of scalar control and starts registering the direction of change of the stator current in the first half of period of a test signal. Depending on change of the stator current the system of its minimization begins developing the γ_1 manipulated signal directed on reduction of the current. When change of the current becomes less than a hysteresis of the relay regulator (Fig. 8, a), the test signal is disconnected until owing to various reasons (change of the load torque, temperature of windings, etc.), not depending on change of a reference speed, slip will not deviate the optimum value that will cause the corresponding increase in the current and, consequently, in the power losses.

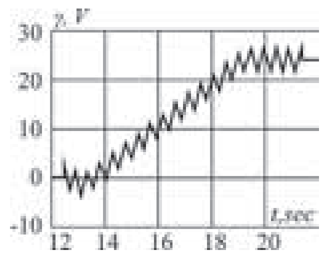
The results of simulation are shown in Fig. 9. The stator current are presented in synchronous frame so that its frequency in Fig. 9 is null.



a



b



c

Figure 9. The stator current (a), overall power losses (b) and additional stator voltage (c)

The analysis of results shows operability of the developed control system. So, with speed twice reduced relative to the rated and load torque one and a half times exceeded relative to the rated, for ensuring the minimum stator current it is necessary to increase the stator voltage. It leads to a simultaneous reduction of power losses (about 20%). The stator current decreases approximately by 15...20%. Speed after shutdown of system of the current stator minimization comes back to the value before inclusion of the system. Oscillations of speed under the search control system are insignificant and do not exceed 0.5%.

Conclusions

The developed automatic temperature regulation system of traction induction motors consists of control unit implemented by P- or PI-controller, executive regulation device implemented by induction motor drive with the centrifugal fan. The developed and constructed physical model of both traction and auxiliary drive of locomotive allows to investigate the thermal and electromechanical and control processes. The developed control system of the induction motor with the stator current minimization provides also power losses minimization. The minimization mode is feasible under the steady state. The control system gives the greatest effect under lowered speed and/or the lowered or raised load torques due to regulation in necessary limits of the stator current by means of change of the stator voltage. Reduction of both power losses and the stator current can reach

20% of initial value depending on the providing speed and torque.

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