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ORIGINAL SCIENTIFIC PAPER

Optimal starting of the induction motor

Oleg Kimstach

Ship electric power systems department, Admiral Makarov National University of Shipbuilding, Ukraine
E-mail: oleg.kimstach@nuos.edu.ua

Abstract. The paper proposes an algorithm to determine a method for an optimal starting of the induction motor. The algorithm is demonstrated by comparing on four simple types of the induction motor starting: direct-on-line starting, star-delta starting, starting with an additional resistance and inductance. The algorithm is based on a comparison of results of a numerical simulation of the starting processes of the induction motor. The dynamic curves are drawn for the stator current, rotor speed and electromagnetic torque of the induction motor. For the starting methods using an additional resistance and inductance, curves of the dependence of the corresponding values on the size of an additional resistance and inductance are drawn. They are calculated by using a classical model of the induction motor in the *u* and *v* axis. The transient time, average current and average power of the induction motor are used as comparison criterion. To define the optimal starting method, the relative estimations method is used. For the considered example, the starting method of the induction motor with an additional inductance is optimal.

Keywords: induction motor, model, starting, electrical circuit, comparison criteria, relative estimations method

Optimalen zagon indukcijskega motorja

Članek predlaga objektivni algoritem za določitev optimalne metode za zagon indukcijskega motorja. Predlagani algoritem je prikazan s primerjavo štirih najpreprostejših vrst zagona indukcijskega motorja: neposredni zagon, zagon zvezde-delte, zagon z dodatnim aktivnim uporom in zagon z dodatnim induktivnim uporom. Ta algoritem temelji na primerjavi rezultatov numerične simulacije začetnih procesov indukcijskega motorja. Dinamične značilnosti so dobljene za statorski tok, hitrost rotorja in elektromagnetni moment indukcijskega motorja. Za začetne metode z uporabo dodatnih uporov se izdelajo značilnosti odvisnosti navedenih vrednosti od velikosti dodatnega upora. Za njihov izračun smo uporabili klasični model indukcijskega motorja v osi *u* in *v*. Kot primerjalna merila so bili uporabljeni prehodni čas, povprečni tok in povprečna moč indukcijskega motorja. Za iskanje optimalne metode zagona je bila uporabljena metoda relativnih ocen. Za obravnavani primer je bil optimalen zagon indukcijskega motorja z dodatnim aktivnim uporom.

1 INTRODUCTION

As known, due to its advantages the induction motor (IM) is widely used for the electric drives [1-3]. However, its using a considerable amount of the starting current causes significant problems for both IM itself and for the power distribution network. The damage of the stator winding insulation due to overheating at a high current is 30 % of all types of the IM failures [4]. IM starting also negatively affects the magnetic core: [5] investigates the deforming mechanical forces in the IM stator magnetic core at its starting. The main problems of the power network at the IM starting are the resulting voltage dips [6-9], imbalance of the three-phase voltage system [10] and high harmonics [11]. Thus, setting up an optimal method for the IM starting is urgently needed.

The paper presents an algorithm to identify an optimal method for the IM starting.

To solve the problem, the mathematical IM modelling method and the criteria and method to compare the IM starting types need to be determined.

To simplify the solution of the problem, [12, 13] use static IM models based on equivalent circuits or only on the value of the IM impedance [14]. Thus produced significant errors can negatively affect the research results. The most common and appropriate tools to research the transient IM processes are simulation models in the *u* and *v* axis [1, 15, 16].

These models are solved by using numerical methods. For this purpose, the following specialized software is widely used: COMSOL [2], ETAP [8], PCCAD [7], etc. The algorithms to solve the IM simulation problems are based on the finite-element methods [2, 17] and the Euler and Runge-Kutt methods [1, 6].

The determination of the comparison criterion is a rather subjective problem. It may depend on the purpose of the electric drive, type and power of the supply network, requirements for the electric energy quality and several other factors. [11] uses the voltage deviation, harmonics and a type of the transient as a comparison criterion, but these criteria are related and do not fully characterize the IM starting transient processes.

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2 IM STARTING METHODS

The IM starting methods are cither direct-on-line (DOL) starting methods, voltage reducing methods or frequency reducing methods.

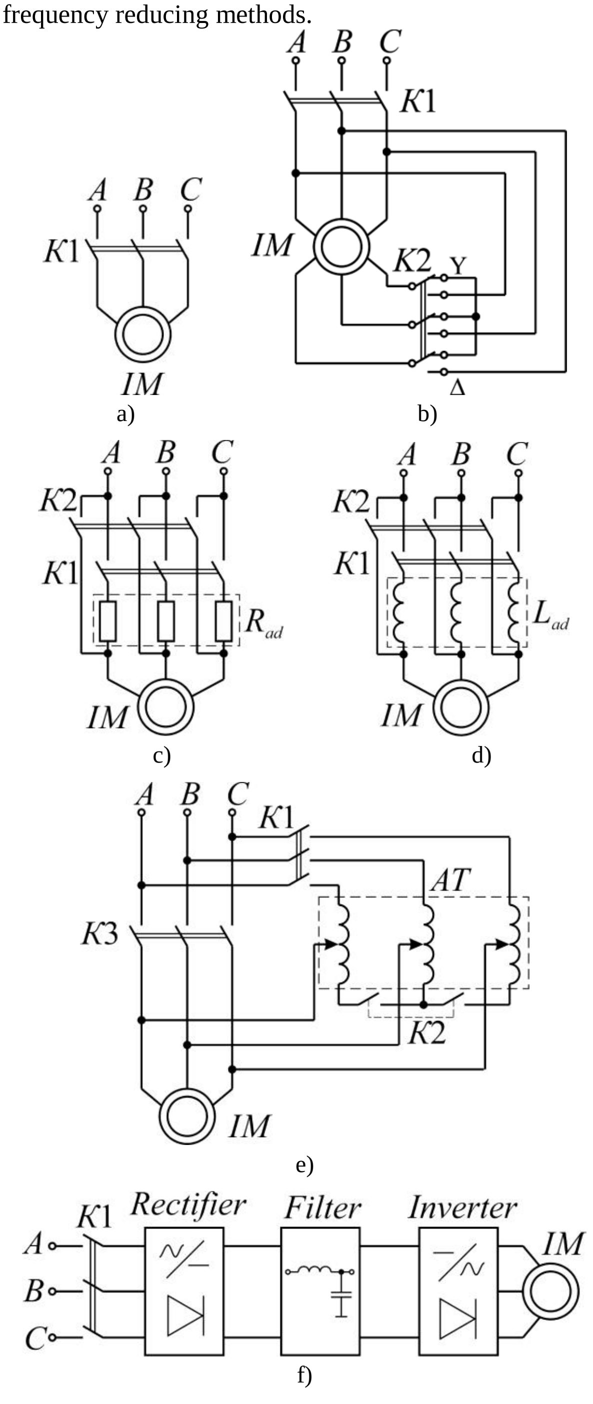


Figure 1. Electric circuits of IM startings:
a – direct-on-line starting; b – star-delta starting;
c – additional resistance starting; d – additional inductance starting; e – autotransformer starting;
f – converter starting

The most widely used method is the DOL starting method. It is particular applied for the low-power IM. The stator current increases up to 5…7 times the rated stator current. It is the simplest type of the IM starting (Fig. 1, a). When the generator or transformer power supplying IM equals its power, the DOL method cannot be used in almost any case.

The star- delta method is the simplest starting method of the voltage reducing methods (Fig. 1, b). At the IM starting the stator winding is connected to the phase voltage. It is in $\sqrt{3}$ times lower than the line voltage. This reduces the IM starting current and also its torque. Therefore, it is better to use this method when the resistance torque equals zero or is of the fan type. The star- delta starting control system can also be used for the IM speed control.

To reduce the stator voltage, an additional limiting resistance (Fig. 1, c) or inductance (Fig. 1, d) is used to find an additional resistance value enabling an optimal relationship between the stator current and the electromagnetic torque.

The autotransformer smoothly adjusts the stator voltage (Fig. 1, e), thus enabling a smooth control of the IM starting stator current. To use this type of IM starting, an additional electric machine, i.e. an autotransformer is needed, which is expensive. Therefore, this type of the IM starting is applicable when the autotransformer is used also for the IM control.

Some electric drives consisting of IM and converter provide a low voltage starting (Fig. 1, f) and at the same time they also decrease the voltage frequency. This type of the IM starting can be realized in controllable drives. Its main advantage is the high starting torque. Another ways of limiting the IM starting current are the use of the wound rotor IM with an additional resistance in the rotor circuit and IM with a pole control. These variants are not used in modern electric drives or item they are too specific for a common application. SFCL can also be used [18], but it is very demanding, and expensive.

The paper investigates the DOL (Fig. 1, a), star- delta (Fig. 1, b), additional resistance (Fig. 1, c) and additional inductance (Fig. 1, d) types of the IM starting for being simple and common.

3 IM MATHEMATICAL MODEL

To simulate the IM starting, the classical model of the generalized electric machine in two axes is used [15]. This type of the model is simple and adequate. The system of voltage equations for the two-phase generalized electric machine in coordinate axes rotating with speed ω_c [15] is:

$$\begin{cases} \vec{V}_s = R_s \vec{I}_s + \dfrac{d\vec{\Psi}_s}{dt} + j\omega_c \vec{\Psi}_s \\ \vec{V}_r = R_r \vec{I}_r + \dfrac{d\vec{\Psi}_r}{dt} + j\left(\omega_c - \omega_r\right)\vec{\Psi}_r \end{cases} \tag{1}$$

where ω_r is the rotor rotating speed; $\vec{V}_s$, $\vec{I}_s$, $\vec{\Psi}_s$, $\vec{V}_r$, $\vec{I}_r$ and $\vec{\Psi}_r$ are the stator and rotor vectors of voltages, currents and interlinkages; R_s, R_r are the stator and rotor resistance.

Equation (1) corresponding to the Kirchhoff's equations for four windings of the generalized electric machine at their interlinkages [15] are

$$\begin{cases} \vec{\Psi}_s = L_s \cdot \vec{I}_s + M_{sr} \cdot \vec{I}_r \\ \vec{\Psi}_r = L_r \cdot \vec{I}_r + M_{sr} \cdot \vec{I}_s \end{cases} \quad (2)$$

where L_s, L_r, M_{sr} are the stator and rotor inductance and mutual inductance.

The IM model is set up by using equations for the generalized electric machine in the *u* and *v* axis [9]. The rotating speed of coordinate axis ω_c is the same as the rotating speed of the stator magnetic field, i.e. p.u. = 1, and therefore in p.u.

$$\omega_c - \omega_r = 1 - \omega_r = s \,. \quad (3)$$

To simplify the definition of the currents from eq. 2, parameters of the reduction equations are used:

$$\begin{cases} c_r = \left(x_m + x_r\right)/x_m \\ c_s = \left(x_m + x_s\right)/x_m \\ a = x_m\left(c_s c_r - 1\right) \end{cases} \quad (4)$$

where x_s, x_r, x_m are the inductive resistance of the stator, rotor and magnetization branch of the equivalent circuit.

Taking into account (4), the current equations are:

$$\begin{cases} i_{su} = \left(c_r \Psi_{su} - \Psi_{ru}\right)/a \\ i_{sv} = \left(c_r \Psi_{sv} - \Psi_{rv}\right)/a \\ i_{ru} = \left(c_s \Psi_{ru} - \Psi_{su}\right)/a \\ i_{rv} = \left(c_s \Psi_{rv} - \Psi_{sv}\right)/a \end{cases} \quad (5)$$

where i_{su}, i_{sv}, i_{ru}, i_{rv}, Ψ_{su}, Ψ_{sv}, Ψ_{ru}, Ψ_{rv} are the currents and interlinkages of the stator and rotor windings in the *u* and *v* axis.

The IM model also contains the equation of the electromagnetic torque and the electric drive.

The equation of the electromagnetic torque [15] is:

$$T = m_1\left(\Psi_{su} i_{sv} - \Psi_{sv} i_{su}\right). \quad (6)$$

The equation of the electric drive [15] is:

$$J\frac{d\omega_r}{dt} = T - T_r \,, \quad (7)$$

where T_r is the resistance torque; J is the total moment of inertia of the electric drive and IM.

Taking into account (3), and (4)…(7), the equations (1), represent the IM model. It is solved by using numerical methods utilising the Mathcad program.

4 COMPARISON OF THE IM STARTING TYPES

To compare of the IM starting types, the algorithm is applied to a 4A180M4Y3 induction motor.

The IM label parameters are: rated power P_{2r} = 30 kW; voltage V_{1r} = 380 V; moment of inertia J_m = 0.23 kg·m^2; stator inductive resistance x_s = 0.068 p.u.; rotor reduced inductive resistance x_r = 0.12 p.u.; main inductive resistance x_m = 3.9 p.u.; stator active resistance r_s = 0.034 p.u.; rotor reduced active resistance r_r = 0.018 p.u.; number of poles $2p$ = 4; rated slip s_r = 0.019; rated efficiency η = 0.91; rated power factor $\cos\varphi_1$ = 0.89.

The IM transient curves are calculated for the DOL, star-delta, additional resistance and additional inductance starting types. For the resistance torque, fan type of the curve is used with 75 % of the rated IM electromagnetic torque.

The DOL starting curves are shown in Fig. 2. The stator current is 7.6 times higher than the rated stator current, thus endangering the stator winding insulation and the power supply network. The main advantage of this type is its short starting period, which is very good for the electric drive.

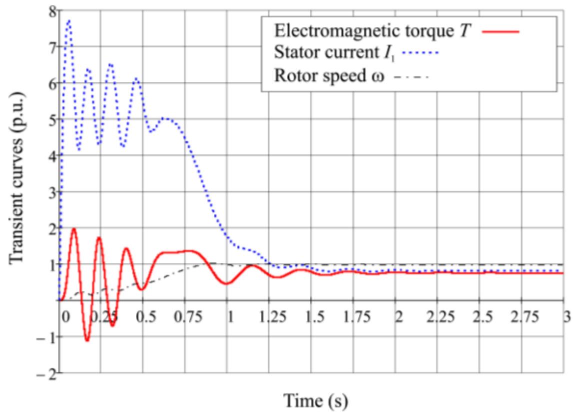


Figure 2. DOL starting transients.

The star-delta starting current is 4.5 times the rated stator current, which better characterizes this starting type (Fig. 3).

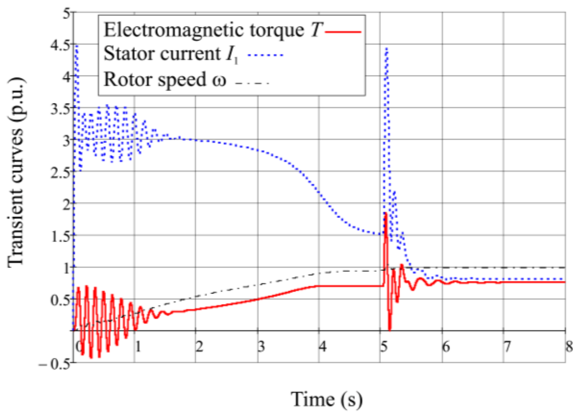
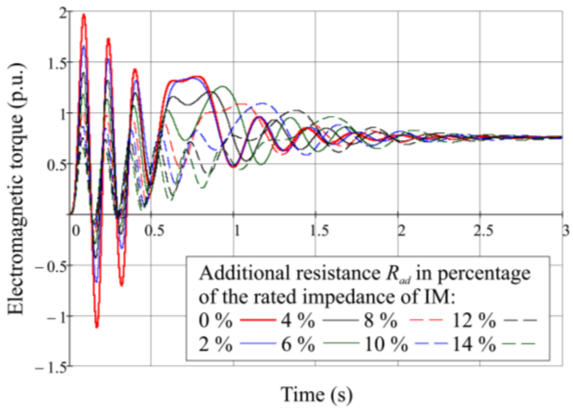


Figure 3. Star- delta IM starting transients.

The current in-rush takes place twice: once at the motor starting and then at reconnecting the motor stator in the delta regime. Both current in-rushes are approximately equal, but in the delta-connection the transient processes vanish quickly. The presence of the two current in-rushes at the star-delta starting produces an additional thermal load on the stator winding insulation. The second current in-rush can overheat the stator insulation. The voltage decrease when the stator winding is connected in the star regime also reduces the starting torque, which does not significantly affect with the fan resistance torque.

The decrease in the supply voltage due to an additional resistance during the IM starting depends on the value of the connected resistance. Therefore, the value of the transients for this type of the IM starting depends on the value of the additional resistance (Fig. 4). It is calculated as a percentage of the rated IM impedance.

The curve types show that the higher the resistance, the longer is the transient process is longer, but the oscillation amplitude of the stator current and torque decreases. Yet, to evaluate the effect of decreasing the stator current, the average current is used for the starting period, to estimate the heating role of the stator winding.



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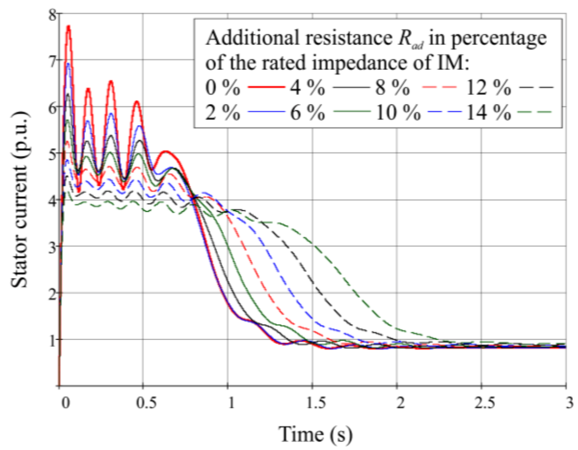

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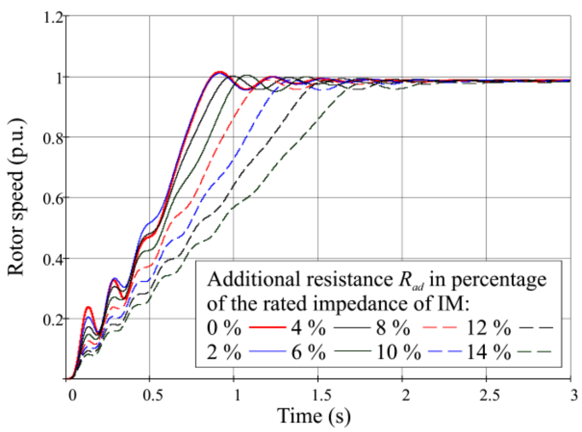


c)

Figure 4. Additional resistance starting transient curves.

Fig. 5 shows generalized characteristics as a function of the value of the additional resistance.

The power indicators of the IM starting are:

- t_{st} is the total starting time for stator current I_s defined by the condition of the final entrance into a five-percent tube deviation relatively to steady current I_{ss} is:

$$0.95\times I_{ss} \le I_s \le 1.05\times I_{ss}\,; \tag{8}$$

- the average current is:

$$I_{av} = \frac{1}{t_{st}}\int_0^{t_{st}} I_s(t)\,dt\,; \tag{9}$$

- the total average real power of consumption is:

$$P_{av} = \frac{m_1\cdot 10^{-3}}{t_{st}}\int_0^{t_{st}} I_s^2(t)\,r_t(t)\,dt\,, \tag{10}$$

where $r_t(t)$ is the IM resistance and additional resistance.

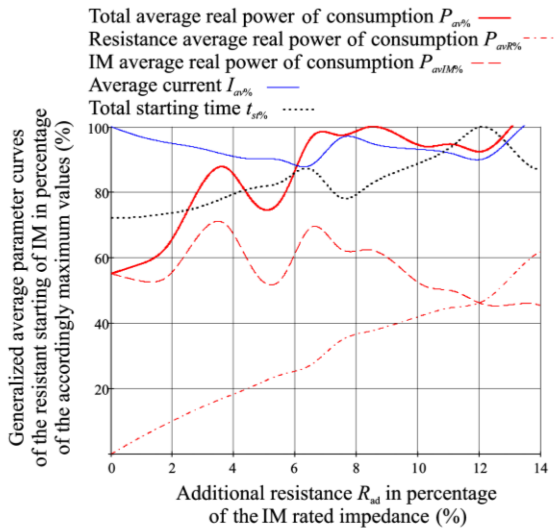
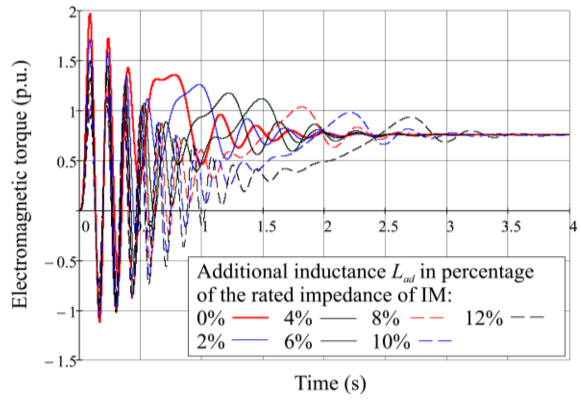


Figure 5. Generalized characteristics of the additional IM starting resistance.

Generalized characteristics (Fig. 5) are shown by using the maximum value scaling. For each curve, all ordinate values are rated as the maximum value of the curve. For IM with an additional resistance starting, it is necessary to separate the real power of the additional resistance from that of IM. In fact, it is necessary to determine at which an additional resistance the average current, the average IM real power, and the starting time are minimal. As these three parameters are non-linear and take different directions (Fig. 5), so, the focus needs to be on one of the parameters. The rest are used as limitations. The average IM real power consumption is used as the main parameter for showing real power losses at the IM starting. The optimal point in the curves (Fig. 5) is the first minimal average power consumption (R_{ad} = 1.2 %), the next two are at the starting time at an additional resistance.

When the voltage is decreased by using an additional inductance, the characteristics also significantly depend on its value (Fig. 6). The advantage of this starting method is that using of additional inductances with a low resistance does not significantly increase the real power losses of the IM starting.



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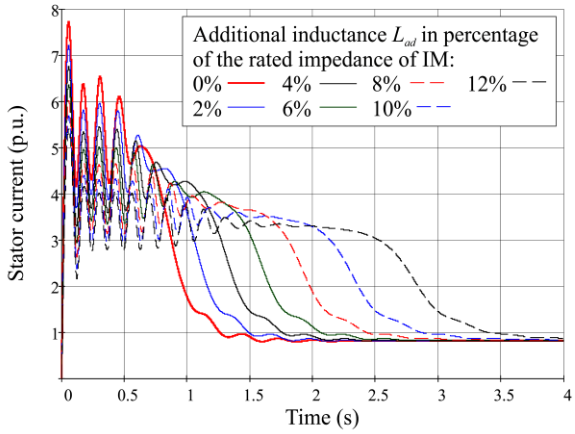

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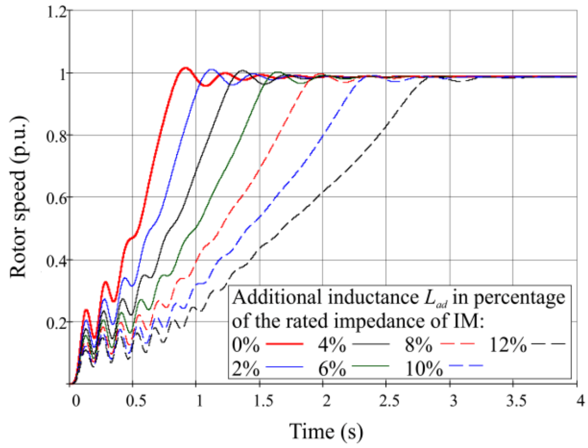

c)

Figure 6. Transient curves of an additional inductance IM starting.

To determine the optimal value of an additional inductance, the generalized characteristics are plotted accordingly to the method of determining an additional resistance (Fig. 7).

Accordingly to the curves (Fig. 7), the minimal average real power at an acceptable value of the IM starting time and average stator current occurs when the additional inductance connected to the stator circuit is 2.8 % of the rated IM impedance.

The optimal method IM starting is the method of the relative comparative estimates [19]. It enables a comparison of different IM starting options based on the analysis of their technical indicators.

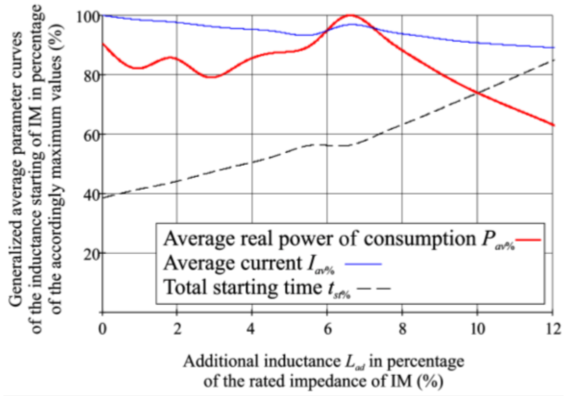

Figure 7. Generalized characteristics of an additional inductance starting.

A partial estimate for the *i*-type IM starting is:

$$K_{i,e} = \begin{cases} K_{e.opt}/K_{i,e} \text{ if } \min K_{i,e} \\ K_{i,e}/K_{e.opt} \text{ if } \max K_{i,e} \\ 1 \text{ if } K_{i,e} = K_{e.opt} \end{cases} \quad (11)$$

where $K_{e.opt}$ is the optimal value of the partial criterion according to the *e*-estimate.

The best option is when the maximum value is 1 and the value of the others is the ratio of the *e*-th estimate (criterion) to either the best or the worst, depending on the type of the search: the maximum or the minimum.

The generalized table 1 shows results for the four types of the IM starting. The difference between the estimates is not very high. Being less than 5 %, the optimal starting type cannot be unambiguously defined. However, the additional inductance IM starting is best estimate due to the following reasons:

- the additional inductance connected to the IM stator winding decreases the stator voltage without producing additional real power losses, thus allowing the IM starting at an acceptable starting time;
- the decrease in the average starting current and the real power consumption are not high, but still enough to prevent the undervoltage in the power network.

Table 1. Comparison of the IM starting types.

Starting type	t_{st}, **s**	I_{av}, **p.u.**	P_{av}, **kW**	**Total estimate**
DOL	1.76	3.12	50	2.32
Y/Δ	5.96	2.47	26.4	2.30
Additional resistance	1.78	3.01	53.5/47.8	2.36
Additional inductance	2.15	3.01	43.8	2.24

The DOL and Y/Δ IM starting have some best estimate values. For the DOL starting, the starting time is minimal and for the Y/Δ starting, the average starting current and the real power consumption are minimal. However, the total estimate of the additional inductance IM starting is the best. The total estimates of the additional inductance and additional resistance types of the IM starting depend on the value of the additional element. So, if another value of the additional element is chosen, the total estimate values will change, too.

5 CONCLUSION

An algorithm is proposed to identify the optimal method of the IM starting. The identification criteria are objective and universal. An example is shown to demonstrate the average advantage of the additional inductance starting.

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Oleg Kimstach received his Ph.D. degree in electrical machines and apparatus from the Odesa National Polytechnic University, Ukraine, in 2003. He is an associate professor at the Ship Electric Power System Department, Admiral Makarov National University of Shipbuilding. He is a Corresponding Member of the Ukraine Technical Sciences Academy. His teaching and research work includes electrical machines, electric power systems, optimal design of electrical equipment and system. He is the author of ninety scientific and training published works.