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FORMING THE INDUCTION MOTOR TORQUE WHEN STARTING

O. Khrebtova
Kremenchuk Mykhailo Ostrohradskyi National University,
Pershotravneva Str., 20, Kremenchuk, 39600, Ukraine.
E-mail: 34092@ukr.net

It is known that when starting some technological mechanisms, the resistance moment can exceed the passport value by several times. The article shows the possibility of forming the maximum possible starting torque with a minimum value of the stator current, proposes the technique for determining parameters of the supply network when creating the maximum possible starting torque for an induction motor. The technique is the following sequence. The magnetization curve and its mathematical image (in the form of a polynomial) are determined for a more precise determination of machine parameters from experimental or passport data. Adequate values of influence factors (voltage and frequency) are determined to create a regression model on the dynamic mathematical model of an induction motor using an iterative method, changing the range and ratio of network parameters. The mathematical calculation of the regression model is performed with obtaining polynomial dependencies for Mn (U, f) and In (U, f) based on a given optimization criterion. The range of variation of U, f is determined from the polynomial Mn (U, f). Equating to the necessary value of the starting torque, from the passport data the author calculates the maximum permissible magnetic flux, with the mathematical dependence Φ = F (Iμ) and determines the value of U and f1 in the saturation region of the engine. The obtained values of the amplitude U and the frequency of the supply voltage f1 meet the optimization criterion In → min. Based on the obtained values of U and f1, the author forms a control signal of a frequency-controlled induction motor to create the necessary starting torque. References 10, table 1.

Keywords: heavy pick-up and start-up conditions, the magnetization curve, the mathematical model, regression mathematical model.

All groups of industrial mechanisms can be conditionally_divided into two classes. *The first class* includes mechanisms, electric machine converting units launched without technological load. *The second class* of mechanisms is characterized by the fact that when starting, the torque is created not only by the forces of friction in the kinematic pairs, but also by the forces of the interaction of the working fluid with the working body (the moment of friction of the pump impeller with water, oil, a liquefied component of mineral raw materials, post-crash starting with technological environment, etc.) [1].

The work [2] prove that a significant part of general industrial and agricultural mechanisms has an initial moment of resistance of the technological unit, which exceeds the rated value of the starting torque during the transition of the electromechanical system from the stationary state to the state of motion (starting torque). This process is accompanied by a change in the forces and moments of resistance according to certain physical and mechanical laws. They are caused to the work of friction forces in the kinematic pairs of the technological mechanism, in the seals, as well as in the zone of interaction of the working body with the technological environment.

Mathematical methods for representing the electric drive of technological mechanisms take into account only standard operating modes without taking into account real individual processes occurring in electromechanical systems, technological mechanisms when starting. Starting as the first phase of an electric drive with various types of load is almost not considered in the educational and technical literature, and the issues of the electric drive dynamics are considered under the condition that the load resistance remains unchanged.

Mathematical dependencies that take into account the peculiarities of starting when performing technological operations with industrial mechanisms are deduced based on the results of the research in the works [3, 4, 5]. The results obtained in these works confirm the stochastic nature of the moment of resistance when starting, which can exceed the nominal value by 2 to 4 times.

The work [3] substantiates the use of the controlled starting systems based on a frequency converter (FC), which allows:

– performing both unidirectional and oscillatory movements of the rotor with a smooth increase in the speed and amplitude of the electromagnetic moment of the induction motor IM;

– choosing the oscillation frequency and spectral composition of the torque of the induction motor to most effectively overcome the increased moment of resistance when starting;

– keeping the working body in a predetermined position in order to carry out preparatory pre-launch or commissioning operations.

However, not all the capabilities of the controlled pull-off system based on the FC – IM are applicable for starting and pre-launch preparation (breaking down the forces of intermolecular bonds of the working medium in the working body) of some technological mechanisms (conveyor lines, hoisting-and-transport mechanisms) [3, 4].

H.I. Shturman considered the issues of the rationality of an induction motor with frequency control with the condition of creating a constant overload ability of the motor when starting as a function of current. As a result of the research, mathematical equations of electrical and electromechanical characteristics are determined depending on the parameters of the supply voltage. Coefficients were introduced into the general expression of the torque of the machine, characterizing the change of IM parameters from the frequency [6] to determine the dependences.

These results are confirmed in [7], where it is justified to take into account the influence of saturation of the magnetic circuit steel and current displacement in the rotor winding to reduce the error in determining the parameters of adjustable electric drives with heavy pick-up and start-up conditions, operating in wide ranges of rotation speed.

H.I. Shturman notes that the realization of the same moments at lower currents is associated with the peculiarity of the quantitative relations of IM parameters, which is clearly manifested near the boundary of the machine's transition from synchronous to asynchronous mode. Starting torque, several times higher than the rated torque, can be obtained in the low-frequency area at a significant voltage, however, the starting current increases. This dependence can be obtained if the supply voltage is not linearly related to the frequency of the supply. The dependence of the starting current in the sliding function with a constant starting torque in the low frequency region has a point $In \rightarrow min$ [6].

The issue of the possibility of creating a significant starting torque with a minimum starting current in the stator circuit by selecting the appropriate voltage-frequency ratio of the supply network arose when starting the induction motor under load.

The purpose of this study is to develop a methodology for determining the parameters of the supply voltage when creating the maximum possible starting torque for an induction motor, with a minimum value of the stator current.

To determine the patterns of the influence of the supply voltage parameters on the IM starting characteristics, the author used the experimental design method (EDM). The EDM input parameters were determined based on IM mathematical model in a three-phase coordinate system. The area of research on the formation of the starting torque in this case lies in the low frequency range.

It is known that ensuring the constant overload capacity of an induction motor with frequency control, the magnetic flux of the machine increases significantly in the low frequency range of 1-15 Hz at high supply voltage, which leads to the saturation of the steel of the magnetic circuit of AM. The saturation mode is accompanied by a significant decrease in the reactance of the magnetization circuit and an increase in the stator current Ic, which can lead to negative consequences. To take into account real physical processes occurring in an AM, it is proposed to use a mathematical model of an asynchronous motor in a three-phase coordinate system with considerations of the saturation of the magnetic core. In paper [8], a results, which confirmed the adequacy of the proposed mathematical model of the asynchronous motors is presented. According to the experimental data, the magnetization curve is approximated, which allows to take into account the saturation of the magnetic circuit. Therefore, the dependence of the mutual inductance parameter $L\mu$ on the magnetization current is introduced into the IM mathematical model. The magnetization curve for IM series 4A can be approximated as follows [9]:

$$\Psi^*(I_\mu^*) = a \cdot acrtg(bI_\mu^*), \tag{1}$$

where $a = 0{,}9932814$, $b = 1{,}4963076$ are the approximation coefficients.

In paper [9], a results, mathematical dependences were considered, which confirmed the dependence of the mutual inductance parameter on the magnetization current, taking into account the dependence of the inductance not only on the magnetization current, but also on the stator current. Based on this, after transformations, the dependence $L\mu^*(I\mu^*)$ in relative units will look like

$$L_\mu^*(I_\mu^*) = \frac{d}{dI_\mu^*}\Psi^*(I_\mu^*)\,. \tag{2}$$

This function has the name of the witch of Agnesi and introduced into the system of differential equations of the mathematical model of an asynchronous motor in a three-phase coordinate system. During the research, the method of mathematical planning of the experiment was applied according to the scheme of rotatable centralized compositional planning, which is based on regression analysis, including the least squares method and statistical data processing. The proposed mathematical model of AM is used to determine the impact factors, such as the frequency and value of the supply voltage.In view of the foregoing ,in designing the experiments the range of variation of factors for the supply voltage frequency is 1 ÷ 10 Hz, and for the supply voltage amplitude is 20 ÷ 192 V. The optimization criterion is the minimum value of the stator current. The experimental error is modeled as normally distributed with parameters $\sigma^2 = 1{,}3$. Confidence probability is defined as the maximum allowable $a = 0.05$. As a result of the implementation of mathematical planning for IM type 4A80B4У3 the author obtains polynomial dependences of the starting torque (3) and starting current (4)

$$M_n(U,f) = a_1 + a_2U + a_3f + a_4U^2 + a_5Uf + a_6f^2\,, \tag{3}$$

where a_1 = -0,0406; a_2 = 0,1488; a_3 = -0,2778; a_4 = 0,0011; a_5 = -0,0111; a_6 = 0,0182 are the coefficients of polynomial dependence (3);

$$I_n(U,f) = b_1 + b_2U + b_3f + b_4fU + b_5U^2 + b_6f^2\,, \tag{4}$$

where b_1 = 2,9373; b_2 = 0,4872; b_3 = -0,6672; b_4 = -0,0018; b_5 = –0,0018; b_5= 0,0234 are the coefficients of polynomial dependence (4).

The adequacy of the obtained model, according to the coefficient of determination R^2, is 99.3282 %. In order to be able to compare models with a different number of factors so that the number of factors does not affect the statistics, the adjusted determination coefficient is usually used, R^2 of which is 98.4885%. Fisher's criterion will be determined as $F_{emp} = 1{,}815$ if $F_{kr} = 3{,}22$. Student's T-test is defined as $t_{emp} = 1{,}25$ at $t_{kr} = 2{,}23$. Thus, the mathematical regression model fully displays the dependence of the starting torque and current on changes in the frequency and voltage of the supply network with acceptable accuracy in the specified range. It should be noted that the polynomial dependences obtained for other types of IM in relative units have deviations between themselves of no more than 2% and fall within the range of permissible accuracy.

As indicated above, a significant starting torque can be obtained in the low-frequency region, the choice of supply voltage parameters for such cases will lead to an increase in magnetic flux, which should not exceed Φ = 1,4 *Фnom*. Based on the results of the study, taking into account the above listed features of blood pressure in the low frequency region to form a given starting torque *Mn =kMk*, where *k* is the overload coefficient (1÷4), the allowable value is determined depending on the parameters of IM, a technique was developed for determining the parameters of the supply voltage.

1. The parameters of the magnetization curve (1) of a given AM are determined.
2. The adequate values of the influence factors (voltage and frequency) are determined on the basis of the mathematical model of blood pressure taking into account (2) for the EDM.
3. According to the given conditions for the MPE, we obtain the dependences for *Mn (U,f)* and *In (U, f)*.
4. Given *Mn* from (3) determine the range of variation of *fc* and *Uc*.
5. From the values of *fc* and *Uc* obtain *Ф = F(Iμ)* provided that *s = 1*.
6. Choose the range of parameters fc and *Uc* where the conditions *Ф(f,U) > 1,4 Фnom ((f,U)* are met.
7. According to (4), with the selected range of supply voltage parameters, the value of *fc* and *Uc* is determined if *In → min*.

Thus, when applying the methodology for determining the parameters of the supply voltage, it is possible to obtain a starting start-up torque with a given overload coefficient, taking into account the saturation region of the magnetic circuit steel with a minimum value of the stator current. The calculation results for the AD type 4A80V4UZ when the stator windings are included in the triangle are given in table.

For example, to provide a starting torque *Mn* = 4*Mnom* at a minimum value of current In, without allowing the motor to saturate, that is, the AM magnetic flux at the saturation boundary, it is necessary to supply a voltage of ≈ 156 V with a frequency of 5 Hz to the IM. If it is necessary to obtain $Mn = 4Mnom$ under the considered conditions, the stator current exceeds the value of the permissible starting current. In this mode, the engine cannot work for a long time, therefore, with such parameters of the supply voltage (table) it is necessary to calculate additionally the operating time of the asynchronous machine to prevent overheating of the rotor windings. A methodology for calculating the IM operating time during pre-launch preparation with current overload was proposed in [10].

Starting torque $M_n = kM_{nom}$, Н · м	Starting torque value $M_{пом}$*, $M_{пом}$ = 10,09Н · м	Frequency value,f_1*, fn = 50 Hz	Supply voltage value, U*, Un = 220 V	Starting current I^*_n =min In = 30,797 A
$k = 4$	4	0,11	0,709	1,006
$k = 3.5$	3,5	0,15	0,700	0,958
$k = 3$	3	0,19	0,682	0,933
$k = 2.5$	2,5	0,185	0,614	0,957
$k = 2$	2	0,17	0,532	0,959
$k = 1.5$	1,5	0,165	0,450	0,914
$k =1$	1	0,16	0,350	0,806

The developed methodology allows using the obtained values of U and f_1 to generate a control signal of a frequency-controlled asynchronous motor to create the necessary starting torque during starting and starting, ensuring trouble-free execution of the process and reducing operating costs.

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ФОРМУВАННЯ МОМЕНТУ АСИНХРОНОГО ДВИГУНА ПІД ЧАС РУШАННЯ

О.А. Хребтова, канд. техн. наук
Кременчуцький національний університет ім. Михайла Остроградського,
вул. Першотравнева, 20, Кременчук, 39600, Україна.
E-mail: 34092@ukr.net

Під час рушання деяких технологічних механізмів момент опору може перевищувати паспортне значення в декілька разів. Показано можливість формування максимально можливого пускового моменту з мінімальним значенням струму статора. Задля уточненого визначення параметрів машини по експериментальним або паспортним даним визначається крива намагнічування та її математичне зображення (у вигляді полінома). На динамічній математичній моделі асинхронного двигуна ітераційним методом, змінюючи діапазон і співвідношення параметрів мережі, визначаються адекватні значення факторів впливу (напруга і частота) задля створення регресійній моделі. За заданим критерієм оптимізації виконується математичний розрахунок регресійної моделі з отриманням поліноміальних залежностей для Mn (U, f) і In (U, f). Діапазон варіювання U, f *визначаємо з полінома Mп (U, f). Прирівнюючи до необхідного значення пускового моменту, за паспортними даними розраховуємо максимально допустимий магнітний потік. З математичної залежності Ф = F (Iμ) визначаємо значення U і f в області насичення двигуна, які відповідають критерію оптимізації Iп → min. За отриманими значеннями U і f формуємо сигнал управління частотно-регульованого асинхронного двигуна для створення необхідного пускового моменту.* Бібл. 10, табл. 1

Ключові слова: важкі умови зрушення і пуску, крива намагнічування, математична модель, регресійна математична модель.

ФОМИРОВАНИЕ МОМЕНТА АСИНХРОНОГО ДВИГАТЕЛЯ ПРИ ТРОГАНИИ

О.А. Хребтова, канд. техн. наук
Кременчугский национальный университет им. Михаила Остроградского,
ул. Первомайская, 20, Кременчуг, 39600, Украина.
E-mail: 34092@ukr.net

При трогании некоторых технологических механизмов момент сопротивления может превышать паспортное значение в несколько раз. Показана возможность формирования максимально возможного пускового момента с минимальным значением тока статора. Для уточненного определения параметров машины по экспериментальным или паспортным данным определяется кривая намагничивания и ее математическое изображение (в виде полинома). На динамической математической модели асинхронного двигателя итерационным методом, изменяя диапазон и соотношение параметров сети, определяются адекватные значения факторов влияния (напряжение и частота) для создания регрессионной модели. По заданному критерию оптимизации выполняется математический расчет регрессионной модели с получением полиномиальных зависимостей для Mп (U, f) и Iп (U, f). Диапазон варьирования U, f определяем из полинома Mп (U, f). Приравнивая к необходимому значению пускового момента, по паспортным данным рассчитываем максимально допустимый магнитный поток, из математической зависимости Ф = F (Iμ) определяем значение U и f в области насыщения двигателя, которые отвечают критерию оптимизации Iп → min. По полученным значениям U и f формируем сигнал управления частотно-регулируемого асинхронного двигателя для создания необходимого пускового момента. Библ. 10, табл. 1.

Ключевые слова: тяжелые условия трогания и пуска, кривая намагничивания, математическая модель, регрессионная математическая модель.

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