UDC 621.3.07
DOI: 10.15587/2312-8372.2018.144612

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# STUDY OF THE INDUCTION MOTOR ELECTRIC DRIVE EFFICIENCY IN TRANSIENTS DURING THEIR ACCELERATION

*Об'єктом даного дослідження є електропривід на базі асинхронного двигуна з короткозамкненим ротором, який працює в режимах частих пусків та зупинок. Такі приводи є широко розповсюдженими, зокрема вони використовуються в електромобілях та гібридних автомобілях, а тому покращення енергоефективності перехідних процесів в них є важливою на сьогоднішній день задачею.*

*Одним із проблемних місць такого електроприводу є значне споживання енергії при перехідних процесах, зокрема під час розгону двигуна. За рахунок високих пускових струмів багато спожитої енергії втрачається на нагрівання обмоток двигуна. Експериментальні дослідження, проведені в даній роботі, довели необхідність обмеження цих струмів. Але таке рішення призведе до зростання часу розгону, а це означатиме, що підвищені струми, хоч і меншої величини, діятимуть протягом більшого проміжку часу. Цей наслідок також викличе зростання втрат енергії. Значить, має бути певна точка оптимуму – час розгону, за який електроприводом буде спожита найменша кількість енергії.*

*Для визначення оптимального часу розгону в ході даного дослідження була розроблена комп'ютерна модель електроприводу на базі асинхронного двигуна з короткозамкненим ротором, який керується пристроєм плавного пуску, що дозволяє рівномірно збільшувати напругу від нуля до номінального значення. Результати досліджень довели, що існує оптимальний час наростання напруги, при якому втрати під час перехідного процесу будуть мінімальними. Ця точка залежить виключно від характеристик системи двигун – приводний механізм і не залежить від величини прикладеного навантаження. Результати цих досліджень можуть допомогти покращити ефективність приводних механізмів, що працюють в режимах частих пусків та зупинок, за рахунок невеликого збільшення часу розгону двигуна та зменшення пускових струмів.*

**Ключові слова:** *асинхронний двигун, пристрій плавного пуску, енергоефективність пуску.*

## 1. Introduction

Electric motors are known for their very high efficiency (80–90 %) compared to other possible drive mechanisms. But it is worth noting that such numbers are valid only for stable operation in nominal modes, while transients, the losses increase significantly. One of the most costly processes is acceleration: in order to reach the required speed, the motor should provide an increased torque, which leads to an increase in current and, accordingly, a quadratic increase in electrical losses. This is especially important for drives operating in intermittent operation, that is, with frequent stops and starts. Such mechanisms include, for example, electric vehicles or hybrid electric vehicles, the energy efficiency of which is one of their key indicators. This confirms the relevance of this work.

## 2. The object of research and its technological audit

*The object of research* is an electric drive based on an induction motor (IM) with a squirrel-caged rotor (Fig. 1), which operates in frequent start and stop modes. This drive consists of:

– power sources (U~), which supplies electrical energy;
– electric energy converter (EEC), which determines the mode of operation of the electric drive due to the energy conversion and control of the output voltage;
– electromechanical energy converter, which is IM;
– load (L).

During transients acceleration of the load is increased, the electromotive force (EMF), directed against the current, which creates a magnetic field of the engine, is reduced, and therefore the currents in the electrical circuit increase greatly. Losses on heating of motor windings grow in proportion to the square of these currents, and hence the efficiency of such an electric drive drops sharply during transients.

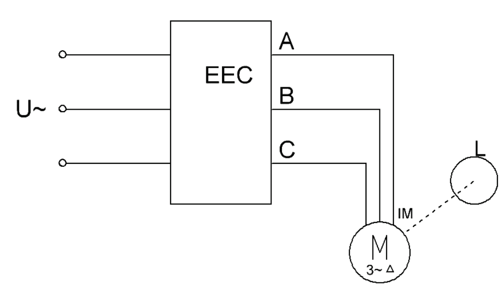


**Fig. 1.** Diagram of the electric drive based on an induction motor with a squirrel-caged rotor: U ~ – power source; EEC – electrical energy converter; IM – induction motor with squirrel-caged rotor; L – load

One of the problem areas of such electric drive is significant energy consumption during transients, in particular during engine acceleration. Due to the high inrush currents

 ISSN 2226-3780

a lot of energy consumed is lost on the heating of the motor windings. In order to reduce losses during acceleration, it is necessary to reduce the starting current. It is possible to achieve by implementing an artificial increase in the transient time. However, if the acceleration lasts too long, it will lead to an increase in energy costs for overcoming the static moment and therefore to an increase in the total static engine heat losses. So, there must be a certain optimal point: acceleration time at which the minimum energy will be consumed.

## 3. The aim and objectives of research

*The aim of research* is finding this optimal point – the acceleration time determined by the control device from which the least amount of energy will be consumed. To achieve this aim it is necessary to:

1. Create a mathematical and computer model of the electric drive with a control system that will set different acceleration times.
2. Experimentally confirm the problem described.
3. Carry out numerical calculations, with the help of which it will be possible to determine the optimal acceleration time and make sure that in this way the energy efficiency of the electric drive can be improved.

## 4. Research of existing solutions of the problem

The study of the energy efficiency of motor starts has been carried out before. Increased losses at start were demonstrated in [1], although it was a synchronous reluctance motor considered there. Ideas for improved starts with smaller losses were proposed in [2, 3], but also only for synchronous motors.

Studies [4] show that for modes of frequent starts and stops, for example, in electric vehicles, an induction motor (IM) would be the most efficient engine. But even choosing to apply IM, energy efficiency during starts can still be improved. For such studies, it is possible to use the methods proposed in [5, 6]. The authors of these works investigate the IM start well, although they do not come to the conclusion how to improve energy efficiency.

Losses in IM during starts can be reduced by reducing the starting current. This is shown in [7, 8]. But a decrease in the starting current leads to a decrease in the starting torque and, therefore, to an increase in the duration of the acceleration [9]. Therefore, it is necessary to find a certain optimal point for the magnitude of the starting current. An example of such complete study is the work [10], in which the answer to the question is clearly given: how can we accelerate IM to the rated speed with the least losses. The only problem with this study is that the implementation of the presented method requires complex motor control systems based on fuzzy logic, which can be expensive for general use.

Thus, the question of finding a simple method to control the energy-efficient IM start, which is investigated in this work, remains promising.

## 5. Methods of research

In a transient mode, the currents flowing in the stator winding of an induction motor (IM) significantly exceed the rated values and cause increased energy losses, and, accordingly, overheating of the motor. The greatest losses are allocated to IM, operating in the mode of frequent starts. The calculation of the IM start includes determining the dependence of the rotational speed on time during acceleration, determining its duration and energy losses in the stator and rotor during the transient process. The total torque on the motor shaft can be represented as a sum of static and dynamic torques:

$$M = M_s + M_d, \quad (1)$$

where $M_s$ – the static torque is the sum of the useful load torque and the torque resistance; $M_d$ – dynamic toruqe, determined by the formula:

$$M_d = J\frac{d\omega_2}{dt}, \quad (2)$$

where $J$ – the moment of inertia of the system of the IM and an actuating mechanism, N·m·s$^2$; $\omega_2$ – the angular velocity of the rotor rotation, rad/s.

The acceleration time of the electric motor is determined by electromechanical processes, since the electromagnetic transients occurring in the engine have a much shorter time constant. The value of the electromechanical time constant $\tau_m$ is determined from the condition of engine acceleration at a static moment on the motor shaft $M_s=0$.

The duration of the motor start is determined by the formula:

$$t_n = \int_0^{\omega_{2w}} J\frac{d\omega_2}{(M^* - M_{st}^*)}, \quad (3)$$

where $M^*=M/M_n$ and $M_{st}{}^*=M_{st}/M_n$ – the relative values of the electromagnetic and static torques; $M_n$ – the nominal torque of the engine; $\omega_{2w}$ – the value of the angular velocity of the rotor rotation, at which the transient acceleration process is considered complete (it takes it as 0.95 of the nominal frequency of the rotor rotation).

Given the large values of starting currents, during engine acceleration static losses (magnetic and mechanical) can be neglected, so the total losses will be determined as the sum of losses in the rotor and stator windings:

$$\Delta W = \int_0^{t_n}(\Delta P_{el2}dt + \Delta P_{el1}dt), \quad (4)$$

where $P_{el2}$ – electrical losses on the active resistance of the rotor winding, W; $P_{el1}$ – electrical losses on the active resistance of the stator winding.

The energy losses in the rotor for the entire period of acceleration $t_n$ from $s=1$ to the rated value $s_n$ are determined by the formula [1]:

$$\Delta W_2 = \frac{J\omega_1^2}{2}\left[\left(1-s_n^2\right) + 2\int_{s_n}^{1}\left(\frac{M_{st*}}{\left(M_* - M_{st*}\right)}\right)sds\right]. \quad (5)$$

The first term of the equation determines the energy losses due to the action of the dynamic torque applied to the motor shaft, and the second to the static one, in order to determine which it is necessary to know the mechanical characteristics of the engine and actuator.

Energy losses in the stator winding during acceleration:

$$\Delta W_1 = 1.16^2\left(\frac{R_1}{R_2'}\right)\Delta W_2 \approx 1.35\Delta W_2, \tag{6}$$

where $R_1$ and $R'_2$ – the active resistance of the stator winding and the reduced resistance of the rotor winding.

## 6. Research results

The most common method of starting low and medium sized IM is direct start. This is due to its simplicity. Studies of the dynamics of such start were carried out on a specially manufactured research stand using the AC electric drive test system. This system allows obtaining the electrical parameters of current and voltage of one phase of the motor and the frequency of rotation of the rotor shaft as a function of time with a resolution of 8 ms.

IM with a squirrel-caged rotor of the brand MS9024 (Italy) with a rated power of 1.5 kW and a rated rotor speed of 1390 rpm was chosen for the study. Dependencies of current, torque, rotational speed and time during direct start are shown in Fig. 2. In the absence of a load on the shaft, the shock values of current and moment reach 16.5 A and 20 N·m, respectively. The acceleration time is 0.13 s.

In Matlab Simulink, a smooth starter (SS) model was developed that provides a linear increase in the voltage of the stator winding circuit from zero to the rated value. Due to this, mechanical loads on the motor and the actuator are reduced, as well as starting currents and losses in the windings. The model is presented in Fig. 3.

The study of energy-saving start modes of the IM MS9024 with a capacity of 1.5 kW, $U_p$=220 V, $n_{2n}$=1390 rpm was carried out for loads on the shaft $M_i$; 0.25$M_n$; 0.5$M_n$; 0.75$M_n$; $M_n$. The rise time of the voltage on the stator winding was 0; 0.05; 0.1; 0.2; 0.3; 0.5; 1, 2 s, the voltage increased from 0 to 220 V.

The analysis of more than 160 start IM modes made it possible to construct the dependences of the consumed energy on the time of voltage rise on the IM stator winding (Fig. 4). A large amount of energy consumed during direct start is caused by large losses, proportional to the square of the starting current. A further increase in the rise time of the voltage to a time of 0.3 s reduces the value of the starting current and to a certain extent limits the energy loss. An increase in the rise time of the supply voltage of more than 0.3 s leads to an increase in energy loss due to a rise of the acceleration time.

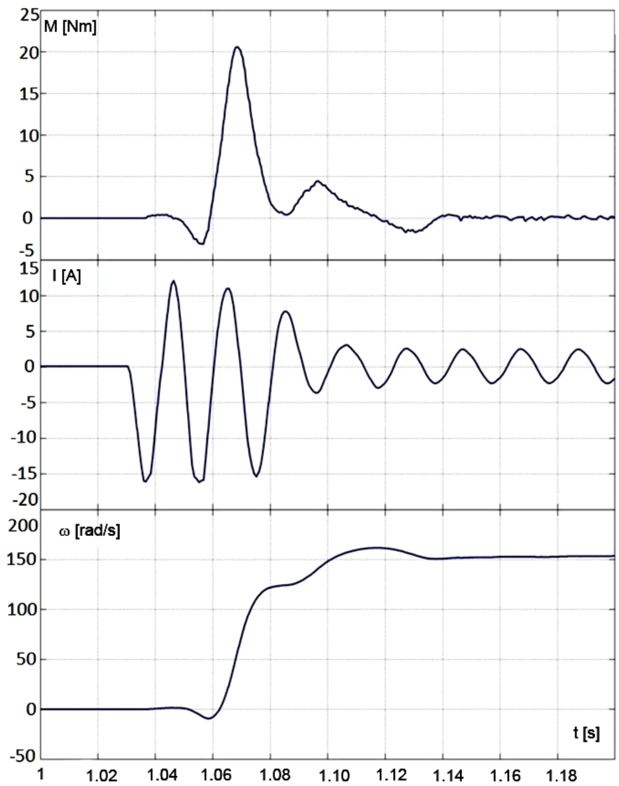


**Fig. 2.** Experimental dependences of torque $M$, current $I$ and rotor rotation frequency ω on time $t$ with a direct start of an induction motor

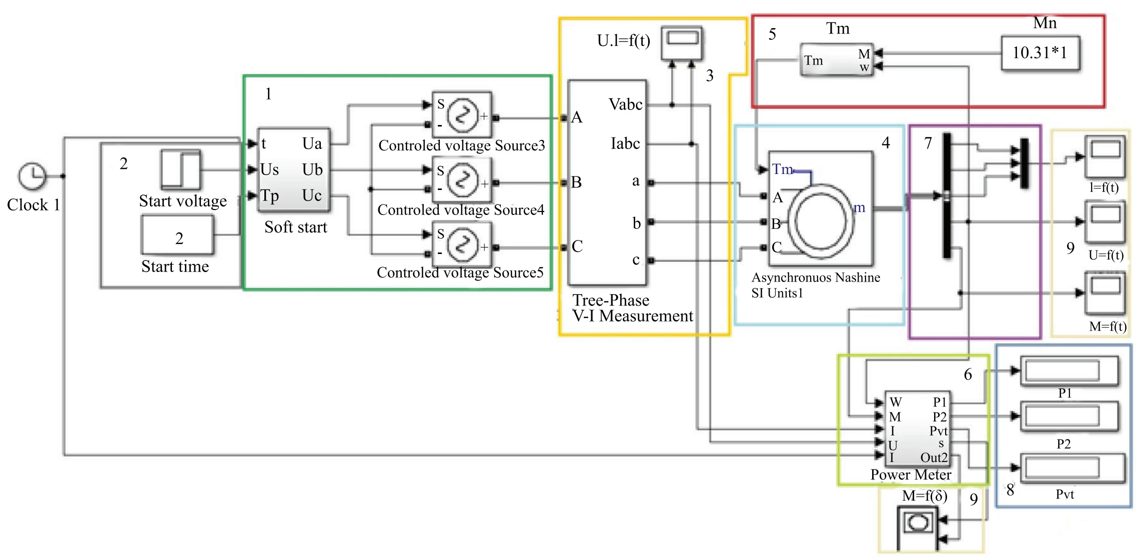


**Fig. 3.** Electric drive model based on an induction motor (IM) with a squirrel-caged rotor with a smooth starter (SS) in Matlab Simulink environment: 1 – three-phase IM power source, regulated by the SS; 2 – units of the SS task; 3 – unit for measuring voltages and currents of the stator circulator; 4 – IM model with a squirrel-caged rotor; 5 – unit for calculating the IM static load torque, which simulates the fan nature of the load, at which the moment on the shaft is proportional to the square of the rotational speed, and also at the rated rotational frequency the rated load is applied to the shaft; 6–9 – units for measuring the electrical and mechanical parameters of the drive

 ISSN 2226-3780

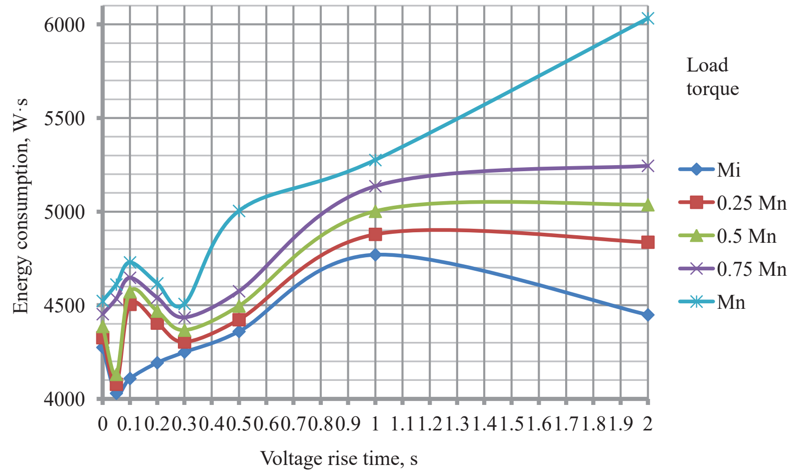


**Fig. 4.** The dependence of the energy consumed by the drive of the set voltage rise time for different values of the load torque at the rated speed

So, as it was foreseen, there is a point of optimal time for the engine to accelerate. This time for this engine – 0.3 s – is determined by the engine's own characteristics and its flywheel moment, which is practically dependent of the mass of the drive mechanism. For other drives with a larger mass of rotating parts, this time will increase. It should be noted that this acceleration time may not be optimal from the point of view of the shock torque. When studying the starting characteristics of other actuators, this factor must be considered. When choosing the start time, it is necessary to take into account the specific features of the specific mechanism, as well as the magnitude of the shock currents and torques.

Fig. 5 shows the dependence of the shock current and the torque of the set voltage rise time.

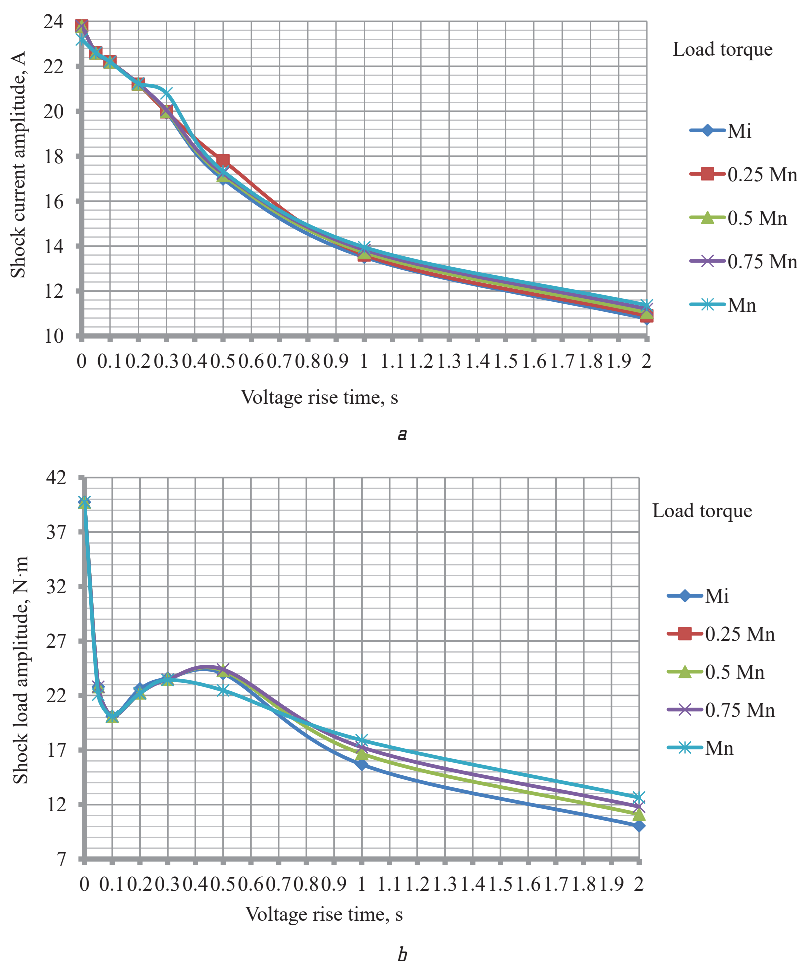


**Fig. 5.** Dependence: *a* – shock current; *b* – torque of the induction motor from the set time of voltage rise

## 7. SWOT analysis of research results

*Strengths*. These studies show that by using a smooth start system and a small increase in engine acceleration time, it is possible to improve the energy efficiency of the electric drive, and thus reduce power consumption and reduce the cost of the engine cooling. The feature determined during the research shows that the optimum point for the engine acceleration time depends solely on the parameters of the engine – drive system and does not depend on the load. This means that SS can be pre-configured by the manufacturer of the drive and will not require any additional actions from its operator. Also, SS is fairly simple to make and use.

*Weaknesses*. At the point of optimum power consumption, the starting torque on the motor shaft is somewhat underestimated. This can lead to the inability to start the drive at elevated loads (for example, excavator). Nevertheless, studies have shown that reducing energy consumption is possible with a less significant decrease in the starting torque, although not as efficiently.

*Opportunities*. These studies were conducted for the most common for such electric drives fan characteristic of the load. However, other features (such as the excavator mentioned above) also deserve attention. In addition, the proposed device smooth starter allows getting only a linear increase in voltage in order to ensure its simplicity. Studies of other growth curves are also interesting and promising.

*Threats*. Despite the demonstrated increase in energy efficiency, the economic rationale for the use of SS was not carried out. And although it was created to be as simple as possible, and electronics is not expensive today, its profitability has not yet been proven. In addition, there are more complex systems [10] that perform this function. And although the system proposed in research is much simpler, it may not be as effective.

## 8. Conclusions

1. In the course of this work, studies were conducted on the energy efficiency of the start modes of IM with a squirrel-caged rotor. A mathematical model of such drive was created, and its computer model was developed in the Matlab Simulink package. A smooth start device is also developed in this package that provides linear increasing of the load voltage from zero to the rated value set by the task time.

2. Experimental studies have shown significant shortcomings of the often used direct start mode. These include increased starting currents of the motor and, as a result, energy losses are significantly increased.

3. In the created computer model, studies were conducted that indicated the direct dependence of the energy consumed by the drive during acceleration on the time of voltage rise. Of these dependencies, a certain optimal rise time of the voltage for the engine, which was studied, was 0.3 s, regardless of the magnitude of the applied load.

The research results may have practical application in mechanisms operating in the regimes of frequent starts. Using a smooth starter, which is configured for a specific drive, it is possible to save energy consumed during acceleration.

#### References

1. Analysis of the starting transient of a synchronous reluctance motor for direct-on-line applications / Castagnini A. et. al. // 2015 IEEE International Electric Machines & Drives Conference (IEMDC). Coeur d'Alene. 2015. P. 121–126. doi: http://doi.org/10.1109/iemdc.2015.7409047
2. A new starting method for 12/8-pole doubly salient permanent-magnet motors without position sensor / Du J. et. al. // 2011 International Conference on Electrical Machines and Systems. Beijing, 2011. P. 1–5. doi: http://doi.org/10.1109/icems.2011.6073672
3. Shehata E. G. Design tradeoffs between starting and steady state performances of line-started interior permanent magnet synchronous motor // 7th IET International Conference on Power Electronics, Machines and Drives (PEMD 2014). 2014. P. 1–6. doi: http://doi.org/10.1049/cp.2014.0281
4. Rahman K. M., Ehsani M. Performance analysis of electric motor drives for electric and hybrid electric vehicle applications // Power Electronics in Transportation. Dearborn. 1996. P. 49–56. doi: http://doi.org/10.1109/pet.1996.565909
5. Analytical method for starting performance calculation of induction motors considering skin effect and leakage flux saturation / Run-hao P. et. al. // 2014 17th International Conference on Electrical Machines and Systems (ICEMS). Hangzhou, 2014. P. 135–138. doi: http://doi.org/10.1109/icems.2014.7013452
6. A study of starting methods for an induction motor using an arbitrary waveform generator / Banerjee A. et. al. // 2015 International Conference on Advances in Electrical Engineering (ICAEE). Dhaka, 2015. P. 34–37. doi: http://doi.org/10.1109/icaee.2015.7506790
7. Habyarimana M., Dorrell D. G. Methods to reduce the starting current of an induction motor // 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI). Chennai, 2017. P. 34–38. doi: http://doi.org/10.1109/icpcsi.2017.8392319
8. Li X., Xu J., Zhang H. Research on torque ramp current limit starting of induction motor based on dsPIC30F6014 // 2017 IEEE 2nd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC). Chengdu, 2017. P. 1627–1630. doi: http://doi.org/10.1109/itnec.2017.8285069
9. The torque oscillation study in the motor soft starting process with discrete variable frequency method / Hu H.-M. et. al. // 2008 International Conference on Electrical Machines and Systems. 2008. P. 1686–1690.
10. Nafeesa K., George S. Starting performance analysis of fuzzy logic based smart motor controller driven induction motor // 2011 International Conference on Energy, Automation and Signal. Bhubaneswar. 2011. P. 1–5. doi: http://doi.org/10.1109/iceas.2011.6147099

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