Methodological problems of replacing low-voltage AC networks with DC networks

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Abstract. The paper discusses the prospects for replacing low-voltage AC power grids of industrial frequency with DC power grids in order to introduce energy-saving equipment and technologies. The modern achievements in the field of energy-saving electric drives are analyzed in detail, which make it possible to introduce constant voltage electric networks attractive for investments. The generalized analysis can be performed using the synergetic criterion of the technical and economic efficiency of innovation. To use such a criterion, all indicators to be analyzed must be presented in dimensionless form. We propose to consider separately the technical and operational groups of the generalized technical characteristics of AC and DC electric drives. The selected subset of groups of parameters of electric drives is justified from the point of view of regulatory and technical documents currently in force. This methodology seems to be more objective than the existing industry methodology for assessing product quality based on functional analogues of products being developed. With a synergetic approach, any characteristic is invariant relative to the others, which confirms the objectivity and reliability of the comparison method. The system of indicators is necessary and sufficient, both for technical assessment and for the creation of new designs and the development of directions for the design of electric drives. In conclusion of this work, we give examples of the implementation of such an approach by comparing the achieved indicators of quality and operational reliability of electromechanical energy converters produced by domestic enterprises.

1. Introduction
In modern conditions, the implementation of commercially successful energy-saving measures is entirely dependent on the depth of elaboration of design decisions and the assessment of existing risks. In addition to the topics already discussed in previous works [1–4], we propose for discussion in the professional community a new methodological approach to the use of direct current power electric drives for general industrial mechanisms instead of alternating current electric drives.

For further analysis, let us consider the general requirements for innovative design solutions.

Firstly, design decisions should be aimed at improving the electrical safety of consumers' electrical units. This is achieved not only by reducing the voltage of the unit to a safe ultra-low level (not more than 48 V) but also by undertaking special measures of protection against electric shock. The list of such measures is well known [5] and does not need additional description and justification for use.
Secondly, design decisions should be energy saving. The possibilities of energy-saving technologies are realized both when reducing losses in the transmission of electric energy and when reducing the power consumption of electric power receivers.

Thirdly, design decisions should ensure the maintenance of the necessary and sufficient level of unification of wiring accessories and electric energy metering devices.

Fourthly, design decisions should increase the reliability of power supply, related both to protection against probable erroneous actions of the consumers, and to protection of electrical equipment from switching and atmospheric interference. For example, the quenching of a constant voltage arc requires special measures, the illiterate use of which can negate all the benefits of energy saving.

Finally, design decisions in the field of DC voltage supply should have the lowest possible implementation cost. An example of cost reduction of, for instance, electrical work is the reduction of the consumption of conductive material while reducing the length of electrical networks, as well as reducing the cost of insulation (DC mains can be performed in the form of bare buses) and others. The absence of special protective grounding conductors PE in the extra-low voltage circuits is also a factor in reducing the cost of electrical work.

A feasibility study for the use of new energy-saving design solutions can be performed according to the criterion of the total cost of ownership of electrical networks and electrical installations. [4].

2. Problem statement

In this paper, we consider the issues of the reasonable replacement of a controlled AC electric drive based on asynchronous electric motors with a squirrel-cage rotor (AC electric drive) by a direct current electric drive (DC electric drive) based on non-contact direct current electric motors (NCDCM) controlled from an industrial frequency AC network through controlled three-phase rectifiers (CR).

![Figure 1. Block diagrams of electric drives: a) direct current with controlled rectifier; b) variable frequency AC drive with pulse-width regulator (PWR); Tr – power transformer; M – electric motor; CR – controlled rectifier; CI – current inverter; FC – frequency converter; CI - current inverter; FC - frequency converter.]

From the wide variety of circuit solutions for converters and electric drive control systems, we selected two most used circuits for analysis:

DC electric drive based on NCDCM with excitation from rotor permanent magnets and CR based on a three-phase thyristor voltage regulator (TVR) without filter capacitor with parametric feedback by EMF (in case of controlling the rotation frequency of the NCDCM);

AC electric drive based on an asynchronous squirrel-cage rotor motor controlled by a frequency converter with the double conversion of the current type (vector control with a PWR current inverter and a CR with a low-pass filter).

Comparison indicators that determine the choice of a particular type of an electric drive, as it was previously indicated in [6], are divided into two large groups of generalized characteristics: technical and operational.
Since 2012, a standard in the field of energy efficiency has been in force for asynchronous electric motors in Russia [7], which was developed in Federal Law No. 261-FZ from 11.23.2009 “On Energy Efficiency ...”. A similar document regarding electric motors and DC drives has not yet been created.

We classified the following as the generalized technical characteristics:

1.1 The electromagnetic power of the electric motor $P_{EM}$;
1.2 The efficiency coefficient ($\eta$ - for a DC electric drive) and (the product $\eta' = \eta \cos \phi$ - for an AC electric drive);
1.3 The maximum developed (long-term permissible) electromagnetic moment of $M_{MAX}$ at nominal load and supply voltage;
1.4 The starting moment, which determines the short-term overload capacity of $M_S$;
1.5 The regulation range of rotation frequency of the output end of the shaft $\Delta D$;
1.6 The rigidity of the mechanical characteristics $\gamma$;
1.7 The overload capacity in short-term operation $K_m$;
1.8 The electromechanical time constant $T_{EM}$;
1.9. The moment of inertia of the rotating parts, reduced to the moment of inertia of the rotor $J_\Sigma$;
1.10 The specific mass per unit of power (or the maximum developed electromagnetic moment).

We attributed the following to the operational characteristics:

2.1 The assigned resource (running hours) in the nominal operating mode according to GOST IEC 60034-1;
2.2 The service life, including the shelf life, as well as the maintainability indicator in accordance with GOST 27.410;
2.3 The resistance to the impacts of multiple mechanical (GOST 17516.1) and climatic (GOST 15543.1) external influencing factors during operation;
2.4 The performance according to the degree of protection of the electric motor outer shell against the penetration of water and solids according to GOST IEC 60034-5;
2.5 The execution according to the installation method in accordance with GOST 2479;
2.6 The level of own vibrations and noise in accordance with GOST 11929 and GOST 20815;
2.7 The heat resistance of electrical insulation in accordance with GOST 8865;
2.8 The indicators of interproject unification of the main units (assembly units), determined in accordance with GOST 23945;
2.9 The indicators of electromagnetic compatibility of AC and DC electric drives with consumer technical equipment in accordance with GOST 32144;
2.10 The cost of manufacturing a unified product, thousand of rubles/kW [8].

3. Justification of the method for solving the problem

The methodology for solving this problem depends entirely on the accuracy of the presentation of the source data.

The operational characteristics of the products are set in the relevant state standards. As the achieved indicators for both types of electric drives, one can use indicators included in the maps of the technical level of products compiled by the engineering and technical services of Russian electric machine-building enterprises at the stages of development work on the creation of innovative products. The procedure for compiling and confirming the indicators included in these documents is regulated by the requirements of GOST 2.116 and is available to any user of the state standard information system (SSIS) of Rosstandart.

An objective review requires the development of uniform criteria for a variety of electric drives. We examined the operational characteristics of electric drives with a power of 1 to 100 kW, powered by three-phase electric networks with a voltage of 380/220 V and a frequency of 50 Hz.

The situation is different with the technical characteristics of the products being compared. There is no point in discussing the generally diverse designs of electric machines without being tied to the requirement indicators, as well as operating modes and conditions of safe operation.
We propose the following conditions for evaluating the generalized technical characteristics of electric drives:

1. An analysis should be carried out for electric drives of the same purpose, expressed in the identity of the operating mode. This article analyzes electric drives of continuous operation (S1 according to GOST IEC 60034-1).

2. When replacing one type of electric drive with another, the parameters of their power source (transformer substation), as well as the length and cross-section of the power transmission lines should not be changed.

3. Design decisions related to the replacement of multi-engine electric drives with a single-engine electric drive or vice versa are not considered.

4. The operating conditions in terms of exposure to factors harmful or dangerous to human health are considered to be constantly valid regardless of the type of electric drive selected.

5. Reliability indices when replacing one type of electric drive with another should not deteriorate. For this reason, DC collector electric motors of all types and designs, including electric motors with electromagnetic excitation, the speed control range of which can be increased by weakening the field of the inductor, are excluded from consideration.

6. Mechanical losses, including friction losses in the bearings, as well as the outer surface of the rotor against the air, will be considered equal for both types of electric drives.

7. The power supply is considered to have an infinitely large power. The voltage of the power source, including CR, which is part of both devices, is assumed to be constant independent on the operating mode of both electric motors and valves. The valves are supposed to be ideal, allowing a switching frequency lying above the industrial frequency range.

8. The highest harmonics of the current and voltage arising in the power supply system are neglected for reasons not related to the operation of CR and CI.

4. Theoretical research results, practical value

The list of generalized technical indicators of both types of the electric drives should be expressed in relative units. Only in this case, it will be possible to operate the list for the analysis of electric drives, regardless of power, rotation frequency, moment, and other parameters.

By means of analysis, let us choose the mechanical characteristic \( M=f(s) \), for which we extend the concept of "sliding" to a DC electric drive. Despite the different physical interpretations of the results obtained using this concept for AM and NCDCM, the generality of the mathematical expressions allows us to obtain reliable quantitative results that are subject to further analysis.

First, we obtain analytical expressions for the mechanical characteristics of drives of both types. Let us consider the following basic models:

a) an NCDCM of "classical" design with excitation from permanent magnets;

b) a symmetric three-phase AM with a squirrel-cage rotor, powered by a three-phase network;

c) a symmetric three-phase AM, powered by a single-phase alternating current network and using a reactive element for starting;

d) an asymmetric two-phase AM powered by a single-phase AC network.

Figure 2 shows the mechanical characteristics of the motors of the basic models, constructed in relative units at the same magnitude of the starting electromagnetic moment \( m_S \).

The expression of the mechanical characteristic for the NCDCM has the simplest form

\[
M^{NCDCM} = m_s - \left( m_s - 1 \right) \omega_s = m_s - m_s \left( 1 - s \right) = m_S S, \tag{1}
\]

where \( S = \frac{s \omega_s - \omega_s}{\omega_o} = 1 - \frac{m_s - 1}{m_s} = \frac{1}{m_s} \) - the nominal slide of the NCDCM in relative units;

\( \omega_s \) - the rotor angular velocity (relative to the nominal angular velocity \( \omega_o \)).
To obtain an expression of the mechanical characteristics of AM in a dimensionless form, we use the well-known Kloss formula:

\[
\frac{M}{M_{\text{max}}} = 2 \left( \frac{1 + \rho s_{kp}}{s_{kp} + s\rho_{s} + 2s_{kp}} \right),
\]

(2)

where \( s_{kp} \) – the critical slide, r.u.; \( \rho = R_{r} / C_{r} R'_{r} \) – the constant coefficient depending on motor parameters.

**Figure 2.** Mechanical characteristics of AM - three-phase \( (M^{III}) \), two-phase \( (M^{II}) \) and single-phase \( (M) \), at different critical slide values.
Additionally, let us suppose that for $s_{kp} \leq 0.3$, the quantities $\rho$ and $s_{kp}$ are mutually independent and the term $\rho s_{kp}$ in (2) can be neglected. Then, for a symmetric three-phase AM we get:

$$M_{III}^* = \frac{m_s (1 + \frac{s_{kp}^2}{s})}{s + \frac{s_{kp}^2}{kp}}. \quad (3)$$

As previously noted, the value $C_i$, which determines the relative voltage drop in the winding of the AM stator for low-power motors ($P_2 < 1$ kW), does not exceed 1.2, and therefore, the product $(2\rho s_{kp})$ will be less than 0.5 for $s_{kp} \leq 0.4$.

A single-phase AM has, in addition to the moment from the direct sequence of the magnetic field $M_d$, the moment of the reverse rotating field $M_r$, determined when the rotating field slides backward $s_r$: $s_r = 2 - s_d$, where: $s_d$ is the sliding of the direct field.

A two-phase AM differs from a single-phase one in that the moment from the reverse field at $0 < s < 1$, which corresponds to the condition for the absence of self-running. In this case, the resulting moment will obviously be negative in this region, the term $2\rho s_{kp}$ will be more than one, and it cannot be neglected in (2) since motors of this type have critical sliding values $s_{kp} \geq 1$.

For further analysis, we will use formulas (1), (3).

Figure 2 shows the mechanical characteristics of AM in all three basic models in the region $0 < s < 1$.

We now turn to the consideration of generalized technical characteristics that are directly related to the mechanical characteristics of NCDCM and AM:

4.1. Rotation frequency control range
Unlike asynchronous motors with a nominal rotation frequency that is a multiple of the synchronous frequency of 3000 rpm, an NCDCM can be designed with a nominal rotation frequency in the range from 100 to 10000 rpm for both general and special applications. As a rule, AM with the number of pole pairs $2p \geq 10$ are not commercially available. According to [9], an NCDCM of modern series can have the number of pole pairs $2p \geq 20$ because modern magnets made of iron alloys with rare-earth elements have noticeably decreased in size compared with previously widely used iron-nickel-cobalt magnets made of Alnico alloys.

Depending on the size, DCM can have an area of "safe" work 2.5-3 times more than AM. The limitation of the control range upward from the nominal rotation speed is determined by the mechanical strength of the rotor, and downward from the nominal rotation speed by poor cooling conditions at low and ultra-low ("creeping") rotation speeds.

The limitation of the range of regulation of AM is associated with a decrease in the maximum moment of an asynchronous motor inversely proportional to the square of the supply voltage and a decrease in overload capacity and multiplicity of the starting moment $m_o$.

Figure 3 shows the ranges of regulation of DCM in comparison with three-phase AM in relative units.

4.2. The rigidity of a mechanical characteristic
By this we mean the following expression:

$$\gamma = \frac{M_{max} - M_s}{s_{kp}}, \quad (4)$$

where $M_{max}$ – the maximum value of the electromagnetic moment developed by the motor; $M_s$ – the synchronous operation moment ($s = 0$).

For DCM we will have: $M_{max} = m_t$; $M_s = 0$; $s_{kp} = 1$, and $\gamma_{NCDCM}$, equal to $m_t$, is a constant value independent of other motor parameters.
For AM, it is necessary to take the derivatives in (3) with respect to $s$ and equating them to zero, determine the values $M_{max}$. It is easy to show that the maximum value of the moment in all cases is achieved at $s=s_{kp}$.

\[ P_{EM\ast}, \text{ r.u.} \]

\[ \begin{align*}
    A &= \text{constant moment control range} \\
    B &= \text{constant power control range} \\
    \omega &= \text{Relative total speed, r.u.} \\
    \omega &_{AC} = \omega &_{DC}
\end{align*} \]

\[ = \text{DC motor} \quad = \text{AC motor} \]

**Figure 3.** Comparison of the areas of "safe" operation of electric motors of direct (DC) and alternating current (AC).

4.3. **Overload capacity**

By overload capacity we mean the ratio:

\[ K_M = \frac{M_{max}}{M_n}, \quad (5) \]

- for NCDCM powered by CR on the basis of TVR $K_M = m_S$.
- for AM controlled by a PWR with a current inverter, the overload capacity should obviously be estimated by the ratio of the maximum moment to the starting moment.

Overload capacity depends not only on the parameters of the motor but, to a large extent, on the characteristics of transistors included in the FC or thyristors included in the TVR. The wider the range of rotational speeds in which the motor should provide maximum power, the better the NCDCM or AM should be adapted to processes that require a constant moment in the entire speed range.
4.4. *The electromechanical time constant*

It is the most important characteristic that determines the dynamic properties of an electric drive [10].

In the system of units adopted in this article for both types of drives we have:

$$T_{EM} = \frac{\omega_n}{\varepsilon_n (m_n - 1)},$$  \hspace{1cm} (6)

where $\varepsilon_n = \frac{M_n}{J_n}$, 1/s² - nominal angular acceleration of the NCDCM or AM with the moment of inertia $J_n$, including elements of the reducer and rotating parts of the electric machine.

Obviously, at the same angular velocities, the outer diameter of the NCDCM rotor is significantly smaller than the diameter of the AM rotor, which means that the electromechanical time constant of the NCDCM will be much less than the time constant of the AM.

It is also clear that for motors of the same nominal power, the value of the multiplicity of the starting moment of the NCDCM will always be higher than that of the AM of the same overall dimensions. In the general case, the losses in the anchor at the same values of the nominal slide will be greater in the NCDCM.

4.5. *Rotor moment of inertia $J_d$.*

DC motors have significantly lower rotational axis heights and the mass of both the rotor and the machine as a whole than asynchronous motors and, therefore, have a lower rotor inertia $J_d$, which is a significant advantage for the use of automatic control systems in electric drives, such as servo systems of all types, as well as in reversible drives, operating in both motor and brake modes.

4.6. *Specific mass per unit of power (or the maximum developed electromagnetic moment)*

It also gives the advantage of NCDCM over AM in electric drives of the same functional purpose. It is difficult to formalize this advantage in the form of any kind of dependence because such calculations are strongly influenced by design decisions on the body parts of both types of motors.

In addition, it should be noted that at present, thanks to the progress of modern materials science, a significant drawback of all NCDCM has been overcome - the high cost, associated primarily with the cost of magnetic materials. Also, the service life of the machine increases when using reliable radio-electronic elements and heat-resistant insulation.

For operation in electrical installations located in areas of humid tropical climates, explosive media, as well as rooms with increased fire or chemical hazards, asynchronous motors are still indispensable.

Asynchronous electric drive has proven its effectiveness in those sectors of the industry that are characterized by aggressive environmental conditions, a high degree of contamination with a variety of chemically aggressive products, as well as in conditions of high humidity.

5. **Results and discussion**

The limits of the article do not allow us to dwell on the current system of state standards in Russia in the field of ensuring the operational reliability of electric motors and electric drives. We only note that standardization in the field of electric machines (class 33 of the All-Russian classifier of industrial products) reflects the requirements for a motor as an object of design in much more detail than the standards in the field of electric drive. To date, there are more than forty current state standards aimed at regulating individual requirements for electric machines, methods for their design, manufacture, and quality assurance during the life cycle. In the class of electric drives (class 42 ОКП), there are only three standards of the type of general technical conditions, two of which were developed in Soviet times and are greatly outdated. This, ultimately, designates the methodology for determining operational characteristics, which is thus based on the characteristics of the electric motors that make up the electric drives.
Figure 4 presents a diagram of the so-called synergetic criterion obtained on the basis of relations (1) - (6) described in the article. The diagram complies with the criteria specified in [11].

The methodology for constructing the diagram is as follows:

1. All generalized technical characteristics are expressed in relative units and plotted as segments from the center of the diagram to the periphery on the corresponding radial lines.
2. The total length of the segment is the same for all axes of the diagram and the length of each axis is taken as a unit. The same value determines the current technical level of development.
3. If in various sources (catalogs of firms - manufacturers of electromechanical equipment, scientific papers, advertising materials) there were discrepancies in the definition of parameters, they were interpreted in favor of the highest indicator achieved.
4. It was assumed that all 20 indicators are equivalent, which is illustrated by the same sector area of the chart.
5. Shaded areas indicate the advantages of one type of electric drive over another in a number of ways. The diagram shown in figure 4 is built for electric motors of two manufacturers:
   - Vladimir Electromotor Plant, part of the “RUSELPROM” Electrotechnical Holding. The plant is an exclusive developer and supplier of induction motors with a height of the axis of rotation of 132 and 180 mm in the power range from 0.75 to 315 kW;
   - Closed Joint-Stock Company “MEL” is an exclusive developer and manufacturer of DC electric motors and electric drives based on them in the power range from 0.1 W to 22 kW.

Table 1 presents the main electromechanical parameters of two electric motors; generalized technical and operational characteristics are presented in figure 4.

Figure 4. Synergetic criteria for selecting the type of electric drive.
Table 1. Basic electromechanical parameters of two electric motors.

| Parameter name (characteristics) | Norm for type |
|----------------------------------|---------------|
|                                 | 4A180M2U3     | DBU250-22000-R09-D11 |
| Nominal power, kW                | 22            | 22                     |
| Nominal rotation speed, rpm      | 3000          | 3000                   |
| Supply voltage, V                | 220/380       | 440                    |
| Current consumption, A           | 41            | 30                     |
| Mode of operation                | S1            | S1                     |
| Starting moment, Nm              | 9.5           | 19.2                   |
| Overall dimensions (diameter x length), mm | 360×450    | 250×280                |
| Weight, kg                       | 151           | 8.5                    |
| The source of information        | www.vemp.ru   | www.mel.vrn.ru         |
| Manufacturing plant              | VEMZ OJSC Vladimir | CJSC “MEL” Voronezh |

6. Conclusion

The methodological approaches presented in the article and the results of their application for constructing a simple and clear graphic model (synergetic criterion) allow us to draw the following conclusions:

1. A DC electric drive in the system for automatically controlling the rotation speed or coordinates of the actuator has a significant advantage in almost all generalized technical characteristics over an AC electric drive, regardless of the power, rotation frequency, operating mode, or other parameters of both electric machine units. A DC electric drive has an advantage over an AC electric drive in nine out of ten characteristics and equality in one.

2. The control range of the rotational speed of a DC electric drive is 3-4 times higher than the similar characteristic of an AC electric drive, which opens up great opportunities for constructing automatic control systems with various properties.

3. The electromechanical time constant, which determines the losses in transient conditions, in a DC electric drive is 2.5-3 times less than the same value for an AC electric drive due to the significantly smaller overall dimensions of the rotating parts.

4. The power-to-weight ratio of the drive is 7-10 times higher for a DC drive. Such a solid “gain” is due to the improvement of the properties of magnetic materials and magnetic systems in general, achieved in recent years.

5. The performance of an AC electric drive for eight characteristics has advantages over a DC electric drive, including the technical resource, the cost of maintenance and maintainability, as well as the level of vibration and noise [12].

6. The best indicators of the interproject unification of AC electric drives are explained by a large number of existing series of electric motors and electric drives, therefore, the development and production of a new AC drive are less expensive [8].

7. There is a tendency towards the gradual reduction in the cost of manufacturing DC electric drives. Reducing the range of permanent magnets with an increase in their output is the main factor in reducing the cost of DC electric drives. In our opinion, while maintaining this trend, AC electric drives will be completely supplanted from the market of high-tech controlled electric drives in the foreseeable future.
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