engineering proceedings

MDPI

Proceeding Paper

On the Possibility of Energy Saving Using a Variable-Frequency Drive–Induction Motor System in a Pneumatic Conveying Device †

Duisenova Sholpan [1], Zhunussova Aiza [1], Amirkulov Bekzat [1], Demessova Saule [2,*] and Yerzhigitov Yerkin [2,*]

[1] Department of Electric Power Networks, Almaty University of Power Engineering and Telecommunications Named After Gumarbek Daukeyev (AUPET), Almaty 050013, Kazakhstan; sh.duisenova@aues.kz (D.S.); a.zhunussova@aues.kz (Z.A.); b.amirkulov@aues.kz (A.B.)

[2] Department of Energy and Electrical Engineering, Kazakh National Agrarian Research University, Almaty 050013, Kazakhstan

* Correspondence: saule.demesova@mail.ru (D.S.); ergigitov.erken@mail.ru (Y.Y.)

† Presented at the International Conference on Electronics, Engineering Physics and Earth Science (EEPES2026), Bandirma, Turkey, 24–27 June 2026.

Abstract

The article examines a "variable-frequency drive–induction motor" system of a pneumatic conveying device from the perspective of improving energy efficiency and enhancing the dynamic characteristics of the electric drive. A structural diagram of the frequency-controlled induction electric drive is presented, transfer functions of the system elements are derived, and its stability is analyzed. The study of the electric drive dynamics is carried out based on mathematical modeling in the MATLAB environment using both symbolic and numerical methods. It is established that the voltage stabilization system of the frequency converter ensures a stable operating mode of the induction motor for various values of the controller parameters. The work also includes the synthesis of control system parameters aimed at minimizing energy consumption. An objective function of energy costs is obtained, and optimal parameters of the frequency converter voltage controller are determined. Numerical modeling demonstrated a reduction in power consumption from 4 kW to 2.89 kW, confirming the effectiveness of the proposed approach. The results of the study indicate that the use of a frequency-controlled electric drive in pneumatic conveying systems makes it possible to increase energy efficiency, improve transient processes, and ensure stable system operation under varying loads.

Keywords: induction motor; variable-frequency drive; pneumatic conveying; energy saving; MATLAB; stability; electric drive

Check for updates

Academic Editor: Teodor Iliev, Ivaylo Stoyanov, Grigor Mihaylov and Selahattin Kosunalp

Published: 3 September 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

In modern conditions of rising electricity costs and increasingly stringent requirements for the energy efficiency of technological processes, the task of rational control of electric drives is becoming especially relevant. According to various estimates, electric drives account for up to 60–70% of the total electricity consumption in industry and the agro-industrial sector. In this regard, particular attention is paid to variable-frequency-controlled induction electric drive systems, which ensure the adaptation of motor speed to changing loads.

Recent studies confirm that the use of variable-frequency drives in induction motor systems significantly improves energy efficiency and enhances the dynamic performance

of equipment. In recent years, research has focused on methods for identifying induction motor parameters and adaptive control techniques aimed at improving control accuracy and reducing energy losses.

A separate line of research is associated with the stability analysis of "variable-frequency drive–induction motor" systems as nonlinear control objects. In particular, a number of studies have shown that linearization of the mathematical model and the construction of structural diagrams make it possible to effectively analyze system stability and synthesize controllers for various operating modes of the electric drive.

Considerable attention in the scientific literature is devoted to energy-saving issues in controlled electric drives. Studies show that the use of frequency control in pumping, ventilation, and conveying systems provides a significant reduction in power losses by optimizing the magnetic and electrical operating modes of the induction motor. At the same time, the effectiveness of energy saving directly depends on the proper selection of control system parameters and the controller structure.

In works devoted to modeling electric drives of transport and compressor systems, the importance of using modern software tools such as MATLAB/Simulink for analyzing transient processes and optimizing control system parameters is emphasized. This makes it possible to take nonlinear effects into account and obtain more accurate estimates of energy performance.

Some studies also highlight the effectiveness of applying variable-frequency-controlled electric drives in technological systems with variable loads, including ventilation and compressor systems, where a significant reduction in energy consumption is achieved while maintaining the required performance characteristics.

Despite the large number of studies, the issues of comprehensive optimization of the parameters of the voltage stabilization system of a frequency converter—taking into account energy-saving and stability criteria for specific technological objects such as pneumatic conveying systems—remain insufficiently explored. Particularly relevant is the problem of synthesizing controller parameters that ensure minimal energy consumption while maintaining stability and the required quality of transient processes.

In this regard, the aim of this work is to investigate the possibilities of energy saving in a "variable-frequency drive–induction motor" system of a pneumatic conveying device based on a stability analysis and the synthesis of the parameters of the voltage stabilization system using mathematical modeling in the MATLAB R2023a environment.

2. Materials and Methods

Due to the rise in electricity prices, the problem of energy saving has become particularly relevant, especially considering that electric drives consume up to 70% of generated electrical energy. The issue of energy saving can be successfully addressed only through the introduction of controlled induction electric drives in various sectors of industrial and agricultural production [1–3].

Figure 1 shows the functional block diagram of an induction motor system based on a variable-frequency drive (VFD) used in a pneumatic conveying installation. The system includes a speed reference input, a voltage controller, a frequency converter, an induction motor, a pneumatic load, and a control loop with feedback.

Figure 2 shows the structural diagram of a variable-frequency-controlled electric drive with a "frequency converter–induction motor" (VFD–IM) system in MATLAB Simulink.

https://doi.org/10.3390/engproc2026154040

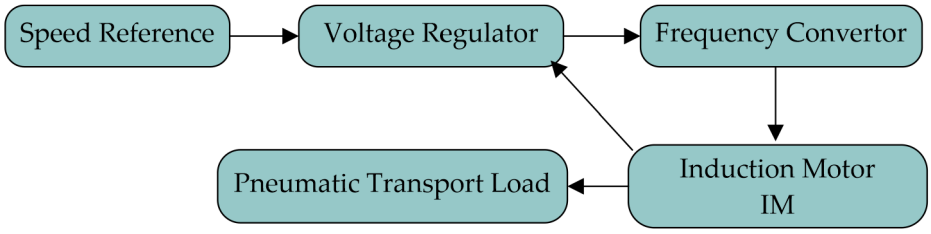


Figure 1. Structural diagram of the system under study.

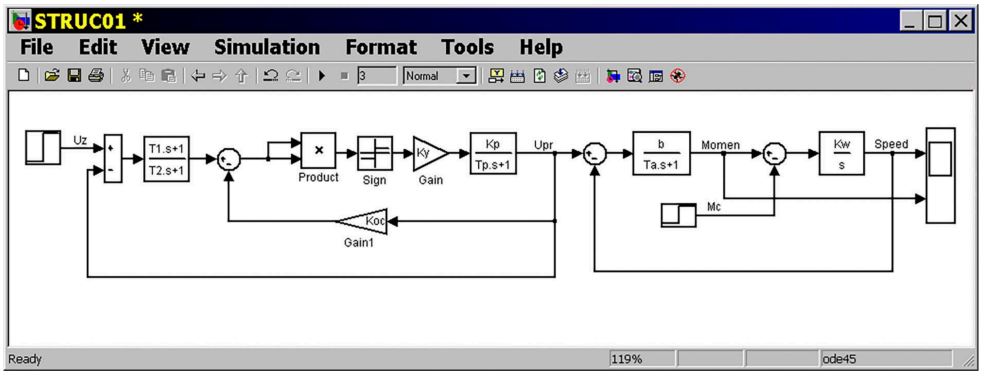


Figure 2. Structural diagram of a variable—frequency-controlled induction electric drive with a VFD-IM system.

In the structural diagram shown in Figure 2, a linearized VFD–IM system is presented, including the transfer functions of the induction motor [1,4–6], enclosed in a unity feedback loop,

$$W_1(s) = \frac{K_W}{s} = \frac{1}{\beta \cdot T_m s} \quad (1)$$

$$W_2(s) = \frac{b}{Tas + 1} = \frac{\beta}{Ts + 1} \quad (2)$$

including the coefficient; modulus of stiffness of the linearized mechanical characteristic of the induction electric drive; electromechanical time constant of the motor; electromagnetic time constant of the stator and rotor circuits of the induction motor; with the transfer function of the frequency converter [1–3]

$$W_3(s) = \frac{Kp}{Tps + 1} \quad (3)$$

including the gain of the frequency converter and the time constant of the frequency converter.

In Figure 2, the multiplying element [4,7], an ideal relay element, and an amplifier with gain, connected in series, represent a substitution for a saturation (limiting) element intended to limit the frequency converter operation in the region of large input signals [1,4,5].

The inertial–accelerating element with the transfer function

$$W_4(s) = k \cdot \frac{T_1 \cdot s + 1}{T_2 \cdot s + 1}, \quad (4)$$

with gain is represented as the voltage controller of the frequency converter (VFD).

When solving the problem of energy saving in a variable-frequency-controlled induction electric drive of a pneumatic conveying system, it is first necessary to determine the stability of the voltage stabilization system of the frequency converter. The stability of motion of the variable-frequency-controlled induction electric drive of the pneumatic conveying system is determined using the MATLAB mathematical environment with symbolic

functions and expressions in terms of the variables of the variable-frequency-controlled induction electric drive [7–9]. Based on the transfer functions (1), (2), (3), and (4) of the structural diagram in Figure 2, we construct symbolic equations of the dynamics of the induction electric drive with a VFD voltage stabilization system. The system of symbolic equations, for a static torque, takes the following form:

$$\begin{gathered} x_1 - w_1 x_2 = 0; \\ x_1 + (1/w_2) - x_3 = 0; \\ x_3 - w_3 \cdot (k_Y \cdot sign((x_4 - k_{oc} x_3)^2) = 0; \\ x_3 - (1/w_4) x_4 - U_Z = 0, \end{gathered} \tag{5}$$

including angular speed of the induction motor; electromagnetic torque of the induction motor; output voltage of the frequency converter (VFD); output voltage of the VFD voltage controller; transfer functions of the VFD–IM system and the VFD voltage controller; gain coefficient; feedback coefficient; and reference input.

The program for determining the stability of the motion of the variable-frequency-controlled electric drive [7–9], shown in Figure 3, is written in the MATLAB programming language.

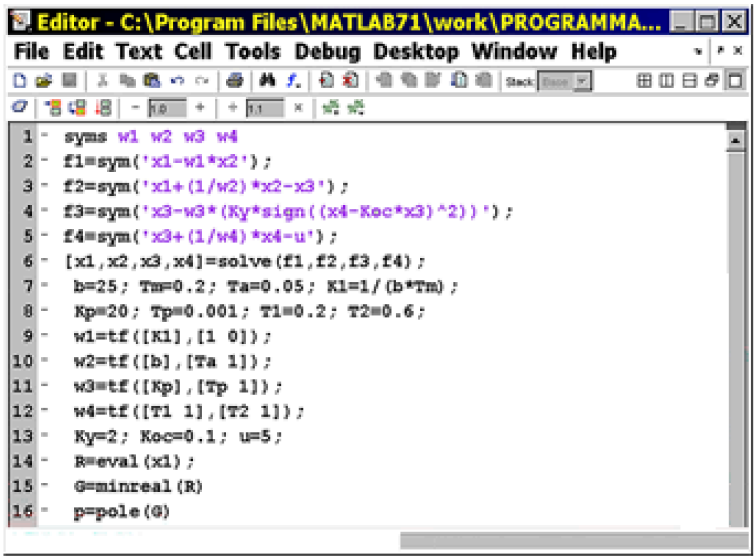


Figure 3. Program for stability analysis.

According to the system of nonlinear symbolic Equation (4) presented in lines 2, 3, 4, and 5 of the program, the solution of the equations is carried out using a MATLAB function, while the transfer functions for each system variable are calculated in symbolic form.

In program lines 7 to 12, numerical values of the transfer functions of the motor, frequency converter, and the time constants of the VFD voltage controller are defined. The coefficients and the reference input are shown in line 13 of the program.

In line 14, the MATLAB function eval(x1) outputs the transfer function, i.e., the ratio of angular speed to reference input. The transfer function and the roots of its characteristic equation, calculated using a MATLAB function, are presented in Figure 4.

As can be seen from Figure 4, all the roots of the characteristic equation of the transfer function have negative real parts; therefore, the motion of the variable-frequency-controlled induction electric drive is stable. In this regard, the reduction in electricity consumption by the controlled induction electric drive can be considered as a problem of minimizing a multivariable function with an appropriate selection of the parameters of the VFD voltage stabilization system.

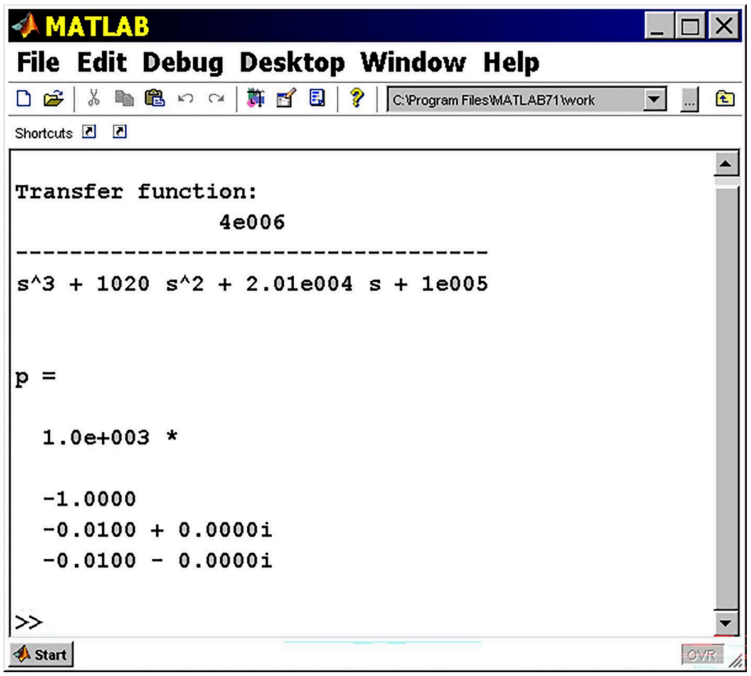


Figure 4. Transfer function and roots of the characteristic equation.

In this case, it is necessary to obtain the objective function of the controlled VFD–IM system. Based on the power equation of the induction motor, the derivation of the objective function is carried out as follows:

$$\frac{dP_W}{dt} = M\frac{d\omega}{dt} + \omega\frac{dM}{dt} \tag{6}$$

$$\frac{dP_W}{dt} = M\left(\frac{1}{\beta T_m}M - \frac{1}{\beta T_m}M_C\right) + \omega\left(\frac{\beta}{T_a}u_{PR} - \frac{\beta}{T_a}\omega - \frac{1}{T_a}M\right). \tag{7}$$

However, after simple transformations and taking into account the equation, Equation (2) takes the following form:

$$P_W = \frac{T_a}{\beta T_m}M^2 - \frac{T_a}{\beta T_m}M_c \cdot M + \beta \cdot u_{PR} \cdot \omega - \beta \cdot \omega^2 \tag{8}$$

or

$$\beta \cdot x_1 \cdot x_3 - \beta \cdot x_1^2 + (T_a/(\beta \cdot T_m)) \cdot x_2^2 - (T_a \cdot M_c/(\beta \cdot T_m)) \cdot x_2 \tag{9}$$

It should be noted that function (8) is the objective function of the problem of reducing energy consumption in a controlled induction electric drive of a pneumatic conveying system [10–12]. It should also be emphasized that, in addition to determining the numerical values of the variables of the objective function, it is necessary to select (synthesize) the optimal parameters of the VFD voltage stabilization system for given numerical values of the feedback coefficient and the system gain coefficient.

The program for synthesizing the parameters of the VFD voltage stabilization system, as well as for determining the gain of the VFD–IM system, is shown in Figure 5. The synthesis program is written in the MATLAB programming language. In the program shown in Figure 5, the quadratic interpolation–extrapolation method and the Runge–Kutta method [7,9,13] are used to solve the problem of reducing energy consumption in the controlled induction electric drive.

```
function programma
global kp; global s2; global s4; global s6;
 n=4; h=0.1; e=0.01;  for i=1:n  a(i)=1; end
 g=0; s1=0; s3=0; s5=0; m=500;
 for i=1:m  j=1;
  while j<30 s=1; while s~=0
   for i=1:n z=a(i); v=mas01(a(1),a(2),a(3),a(4));
    a(i)=z-h; w=mas01(a(1),a(2),a(3),a(4));
    a(i)=z+h; u=mas01(a(1),a(2),a(3),a(4));
    t=w*(2*z+h)-4*v*z+u*(2*z-h); t=t/(w-2*v+u)/2;
    if abs(t-z)<=e s=0;end
    a(i)=t; c1=a(1);c2=a(2);
    c3=a(3);c4=a(4);  end;
    if s==0  break; end; end;
    j=j+1; end;
    s1=s1+kp; s2=sqrt((s1/m)^2);
    s3=s3+T1; s4=sqrt((s3/m)^2);
    s5=s5+T2; s6=sqrt((s5/m)^2);
    g=g+1;
    if g>=m break;end
 end
  disp(' Результаты счета ');
  kp=s2; T1=s4; T2=s6;
  disp('kp='); disp(kp)
  disp('T1='); disp(T1);
  disp('T2='); disp(T2);
  x0=[c1;c2;c3;0];
  [T, X]=ode45(@urav1, [0 2],x0);
  plot(T, X(:,1)*8,'r.-',T, X(:,2),'b.-')
   grid
 function dy=urav1(t,y)
   dy=zeros(4,1);
   u1=5; Ky=5; Koc=0.1;
   Tp=0.001; T1=s4; T2=s6;
   dy(1)=0.2*y(2)-8;
   dy(2)=500*y(3)-500*y(1)-20*y(2);
   dy(3)=(kp/Tp)*(Ky*sign((y(4)-
       Koc*y(3))^2))-(1/Tp)*y(3);
   dy(4)=(1/T2)*u1-(T1/T2)*dy(3)-(1/T2)*y(3);
   Pw=y(1)*y(2); end;
   disp('Pw='); disp(Pw);
 function q=mas01(x1,x2,x3,x4)
    kp=rand*30; T1=rand; T2=rand*0.1;
 q=(25*x1*x3-25*x1^2+0.01*x2^2-0.2*x2)^2;
end
end
```

Figure 5. Program for calculating the parameters of the controlled VFD-IM system.

3. State of the Problem and Research

As a result of the numerical simulation of the variable-frequency-controlled induction electric drive of a pneumatic conveying system in the MATLAB environment, the following main results were obtained.

It has been established that the "variable-frequency drive–induction motor" system remains stable over the entire range of variation in controller parameters. The roots of the characteristic equation lie in the left half of the complex plane, which confirms the asymptotic stability of the system.

During the synthesis of the parameters of the voltage stabilization system of the frequency converter, the following values were obtained: frequency converter gain Kp = 14.7K_p = 14.7Kp = 14.7; time constant of the first channel T1 = 0.5028T_1 = 0.5028T1 = 0.5028; time constant of the second channel T2 = 0.0476T_2 = 0.0476T2 = 0.0476.

The transient responses of speed and electromagnetic torque show: an absence of overshoot; a reduction in the transient time; smooth establishment of the steady-state regime.

In steady-state operation, the motor power consumption is P = 2.89P = 2.89P = 2.89 kW, which is lower than the rated power of the base motor 4A112MV6U3 induction motor

(4 kW). It is established that reducing the control voltage of the frequency converter leads to a decrease in stator current and, consequently, to a reduction in active power losses.

4. Discussion

The obtained results confirm the effectiveness of using a variable-frequency-controlled electric drive for pneumatic conveying systems. The reduction in power consumption is explained by the optimization of the operating mode of the induction motor under variable load.

From the standpoint of electric drive theory, the reduction in energy consumption is associated with a decrease in magnetic and copper losses when the motor operates in a partial excitation mode. This is consistent with well-known principles of electromechanics and studies on energy-saving operating modes of induction motors.

Particular importance is given to the stability of the system under variations of controller parameters. The results show that the system maintains stability even with changes in gain coefficients, which increases its practical applicability.

As a result of running the parameter synthesis program, graphs of the transient processes of speed and torque of the induction motor are displayed on the computer screen (Figure 6).

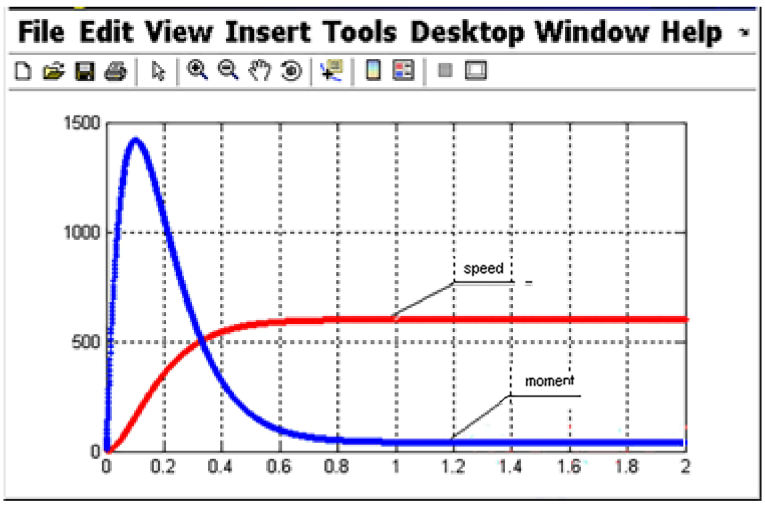


Figure 6. Graph of transient processes of speed and torque of the induction motor. Transient responses of the induction motor speed and electromagnetic torque. The blue curve represents the angular speed of the induction motor, while the red curve represents the electromagnetic torque.

As can be seen from Figure 6, the angular speed curve of the induction motor is obtained without overshoot, which also contributes to energy saving during the startup of the electric drive. As a result, the calculated motor power consumption is 2.89 kW, which is lower than the power of the base motor 4A112MV6U3 (4 kW) used for the synthesis problem. The obtained parameters of the controlled VFD–IM system make it possible to save electrical energy in the steady-state operating mode of the induction motor [4,12,14,15]. To obtain the required parameters that ensure a power value less than 4 kW, the program (Figure 4) is run multiple times until the condition is satisfied.

5. Conclusions

In this work, the "variable-frequency drive–induction motor" system of a pneumatic conveying installation has been studied in order to evaluate its dynamic properties and energy-saving capabilities under frequency control. Based on the structural modeling and

the transfer function analysis, the main operating characteristics of the electric drive in a controlled mode have been established.

The stability analysis showed that the system, with the selected controller parameters, maintains asymptotic stability since all the roots of the characteristic equation lie in the left half of the complex plane. This confirms the correctness of the chosen control structure and the possibility of its practical implementation in industrial pneumatic conveying systems.

The synthesis of parameters for the voltage stabilization system of the frequency converter made it possible to improve the dynamic characteristics of the electric drive: transient processes become aperiodic, overshoot is eliminated, and the settling time is significantly reduced. This indicates improvements in control quality and stability of operation under varying loads.

The results of numerical modeling in MATLAB show that the use of variable-frequency control ensures a reduction in the power consumption of the induction motor from 4 kW to 2.89 kW. The achieved energy-saving effect is due to the optimization of the motor operating modes, a reduction in the stator currents, and a decrease in the total electrical losses.

It was also found that the proposed approach not only reduces energy consumption but also increases the reliability of the electromechanical system by reducing dynamic overloads and thermal stress on the motor windings. This is particularly important for pneumatic conveying systems operating under variable and random loads.

Thus, the use of a "variable-frequency drive–induction motor" system in pneumatic conveying installations is an effective technical solution that provides a comprehensive improvement in energy efficiency, enhanced dynamic performance, and reduced operating costs. The obtained results confirm the feasibility of further research in the field of adaptive and intelligent control of electric drives, as well as expanding the application of variable-frequency-controlled systems in industry and the agro-industrial sector.

It should also be noted that the obtained results can be used in the design of energy-efficient control systems for electric drives not only in pneumatic conveying installations but also for a wide class of technological objects with variable loads, such as ventilation, compressor, and transport systems. The universality of the proposed approach is determined by the use of a linearized model and the possibility of adapting controller parameters to specific operating conditions.

From a practical point of view, an important result is the confirmation of the effectiveness of combining mathematical modeling and numerical optimization methods in the MATLAB environment for synthesizing parameters of electromechanical systems. This significantly reduces design time and improves the accuracy of controller tuning according to the energy minimization criterion.

In addition, the identified relationship between control system parameters and the level of energy consumption can be used for further development of adaptive and intelligent control algorithms based on self-tuning and load prediction principles. This opens prospects for transitioning from classical PID controllers to more advanced optimization-based and neural network control structures.

In conclusion, the conducted research confirms that the implementation of variable-frequency-controlled electric drives is one of the most promising directions for improving the energy efficiency of modern technological systems, and further development of this approach is associated with the integration of optimal control methods and digital modeling.

Author Contributions: Conceptualization, D.S. (Duisenova Sholpan) and Z.A.; methodology, A.B. and D.S. (Demessova Saule); software, D.S. (Duisenova Sholpan) and Y.Y.; validation, D.S. (Demessova Saule) and Y.Y.; formal analysis, D.S. (Demessova Saule); investigation, D.S. (Duisenova Sholpan) and Y.Y.; resources, Z.A. and A.B.; data curation, D.S. (Demessova Saule) and A.B.; writing—original draft preparation, D.S. (Demessova Saule), Y.Y. and A.B.; writing—review and editing, D.S. (Duisenova

Sholpan); visualization, Z.A. and A.B.; supervision, D.S. (Demessova Saule); project administration, D.S. (Demessova Saule); funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeyev, Almaty, Republic of Kazakhstan. No specific grant or funding number was assigned to this study.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ahmed, H.; Cárdenas-Lailhacar, C.; Sherif, S.A. Energy Optimization of Motor-Driven Systems Using Variable Frequency Control, Soft Starters, and Machine Learning Forecasting. *Energies* **2025**, *18*, 5135. [CrossRef]
2. Darkenbaeva, E.; Balbaev, G. Optimization of Components of the Traction Asynchronous Electric Drive Control System. *Bull. KazATC* **2023**, *124*, 384–396. [CrossRef]
3. Song, J.; Li, H.; Hao, J.; Zhai, S.; Xie, H. Study on electricity saving fuzzy controller of asynchronous motors based on fuzzy logic. ICEMS'2001. In Proceeding of the Fifth International Conference on Electrical Machines and Systems (IEEE Cat. No.01EX501), Shenyang, China, 18–20 August 2001; Volume 2, pp. 774–777. [CrossRef]
4. Petrushin, V.; Plotkin, J.; Almuratova, N.; Mustafin, M.; Zharkymbekova, M. Discounted Costs Range Criterion Modification for Controlled Asynchronous Electric Drives. *Energies* **2023**, *16*, 5704. [CrossRef]
5. Shonin, O.B.; Pronko, V.S. Energy-efficient control of asynchronous motor drive with current refinement of the loss minimum on the basis of fuzzy logic. *J. Min. Inst.* **2016**, *218*, 270–280.
6. Sokolova, E.M.; Moshchinsky, Y.A. Evaluation of the Efficiency of Classical Control Laws for Adjustable-Frequency Induction Motors. *Elektrichestvo* **2019**, *12*, 14–20. [CrossRef]
7. Kodkin, V.; Anikin, A.; Baldenkov, A. Optimization of Traction Electric Drive with Frequency Control. *World Electr. Veh. J.* **2025**, *16*, 139. [CrossRef]
8. Mustafin, M.; Almuratova, N.; Darimbayeva, N.; Daurenova, G. Mathematical model of asynchronous frequency controlled electric drive for different types of load. *Eng. J. Satbayev Univ.* **2021**, *143*, 199–206. [CrossRef]
9. Chen, J.-X.; Fan, G.-X.; Li, X.-G.; Mao, Z.-Z. Stability Analysis for DC Motor Drive Systems with Time Delays. In Proceeding of the 2022 34th Chinese Control and Decision Conference (CCDC), Hefei, China, 15–17 August 2022; pp. 2942–2947. [CrossRef]
10. Amanbek, D.; Bussyurmanova, E.; Khairusheva, A. Stability Analysis of Regulated AC Drive Using MATLAB. *Bull. KazATC* **2022**, *121*, 369–377. [CrossRef]
11. Mencou, S.; Ben, M.; Yakhlef, E. Advanced control of induction motors (2019–2025): A comprehensive review of strategies, algorithms and sensorless techniques. *E-Prime-Adv. Electr. Eng. Electron. Energy* **2025**, *14*, 101098. [CrossRef]
12. Zuev, S.; Prokhorov, D.; Maleev, R.; Timoshenko, A.; Ermoshin, A. Analysis of Frequency-Controlled Asynchronous Motor Parameters in Electric Vehicle Electric Drive Control Systems. In Proceeding of the 2024 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SYNCHROINFO), Vyborg, Russian Federation, Vyborg, Russian, 1–3 July 2024; pp. 1–5. [CrossRef]
13. Huang, A.Q.; Chen, C. Converter PWM Switch (CPS): A New PWM Switch Concept. *IEEE Trans. Power Electron.* **2026**, *41*, 185–189. [CrossRef]
14. Vasilev, B.; Korolev, N. The Optimization Potential in Terms of Energy Efficiency for an Asynchronous Electric Drive Through Voltage and Frequency Control with Its Technical Condition. *Energies* **2026**, *19*, 2854. [CrossRef]
15. Paramo-Balsa, P.; Roldan-Fernandez, J.M.; Semião, J.; Burgos-Payan, M. Estimation of Power Output and Efficiency of Induction Motors: A New Non-Intrusive Approach. *Sensors* **2025**, *25*, 754. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.