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Improving Energy Efficiency in Metalworking Machine Tools: Vector Control of Electric Drives Using a Frequency Converter and System Modeling †

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Abstract

Today, the mechanical processing and treatment of metals are of great importance in the development of industrial sectors. Therefore, in the process of mechanical metalworking, a need arises to create new modern equipment or improve existing devices. In industrial sectors, there are several problems with devices and machine tools (such as the 1K62 lathe-screw cutting machine) used in the mechanical processing of metals, including the turning of cylindrical and conical parts, machining their external and internal surfaces, thread cutting, and surface polishing. Specifically, it is difficult to precisely control the spindle speed during the metal-cutting process; energy consumption is high due to the high starting current (5–7 times the nominal value) of asynchronous motors during machine operation; the vibration level is high during operation; and there is no torque control. These problems can be eliminated by using scalar (simple) and vector control methods of frequency converters. In this case, the vector control method was used in the research because it has several advantages as a solution to these problems. As a result, it was demonstrated during the research process that the spindle speed can be reduced to 12.5 rpm. This made it possible to precisely control the spindle speed, maintain torque at low speeds, increase energy efficiency, reduce the load on mechanical transmissions, and ensure the stability of the cutting process. In addition, by operating the asynchronous electric motor through a frequency converter, it is possible to increase the efficiency and service life of such machine tools. This is of significant importance in the process of optimizing the electrical power supply system of the machine tool.

Keywords: frequency converter; spindle; torque; scalar control; vector control; optimization; asynchronous electric drive; modeling

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1. Introduction

In the era of advancing trends in mechanical engineering, there is a growing interest in modern technology capable of minimizing the need for maintenance personnel during the operation of mechanisms [1]. In light of these trends, there is a demand for the development and adaptation of advanced automated electric drive systems [2,3].

In the field of machine tool construction, there is a tendency toward equipping metalworking machines of a universal category with electric drives featuring variable speeds [4–6]. Stepless speed control is achieved through the implementation of asynchronous electric motors with adjustable rotational frequency [5,7]. This has become possible due to significant progress in the development of controllable electric drives, which possess advanced technical capabilities and are characterized by long service life, high reliability, and moderate cost. At the same time, the use of such an approach significantly simplifies the mechanical part of the drive [8,9], namely the gearbox and feed mechanisms, and under certain conditions allows for their complete elimination.

Lathes are considered key equipment in production facilities [10]. These machines, designed for processing cylindrical-shaped workpieces, enable the execution of main technological operations: turning—for external modification of parts—and boring—for internal machining. In addition to these primary operations, lathe-type equipment is capable of performing a wide range of other processes, including threading, drilling, countersinking, and other operations. The tools used for these processes are diverse: cutting tools are used for turning and boring, drills are required for making holes, and taps and dies are used for thread forming. The core component of a lathe machine is the spindle, whose function is to provide rotation to the workpiece mounted for processing [11].

The aim of this work is to improve the efficiency of the 1K62 lathe machine by enhancing its electric drive system. While existing studies explore the general application of variable frequency drives and automated systems in machine tools, they often lack a specific focus on the comprehensive mathematical modeling required for the modernization of legacy equipment. Compared to previous works that predominantly analyze simple scalar control or generic vector control without hardware specifics, the originality of our study lies in the detailed mathematical modeling and practical adaptation of a vector control system tailored specifically for the electromechanical characteristics of the 1K62 lathe. Furthermore, our contribution involves the targeted integration of the highly efficient AIR M132M4 squirrel-cage induction motor and the Schneider Electric Altivar ATV71HD11N4 frequency converter. The study involves controlling an asynchronous motor using a frequency converter [4,12], in particular applying the vector control method, which enables precise regulation of spindle rotational speed, maintenance of torque at low speeds, reduction in energy consumption, and improvement of cutting process stability.

2. Materials and Methods

2.1. Object of Study and System Description

The 1K62 screw-cutting lathe is a universal-type machine manufactured by the "Krasny Proletary" Moscow Machine-Tool Plant (Moscow, Russia). As one of the most widely used industrial lathes, this specific model (1K62) features a maximum workpiece turning diameter of 400 mm over the bed and 211 mm over the cross slide, with a center height of 215 mm, and is manufactured with distances between centers ranging from 710 to 1400 mm [10]. Its robust cast-iron construction and high mechanical rigidity make it highly resistant to vibrations during intensive metalworking processes.

Figure 1 shows an image of the 1K62 screw-cutting lathe machine.

The bed of the machine has a box-shaped structure with transverse U-shaped ribs and features two hardened prismatic guideways. The front guideway is used for the movement of the carriage, while the rear guideway is used for the movement of the tailstock [10].

The 1K62 lathe is an indispensable machine for performing a wide variety of turning operations, such as cutting threads of different standards—metric, modular, inch, and pitch threads—using either a chuck or centers for workpiece fixation. The 1K62 series machines are capable of machining hardened workpieces made of heat-resistant or tool steels that

require intensive cutting conditions. It is noted that such materials are processed under impact loads; however, this does not reduce the accuracy of the performed operations.

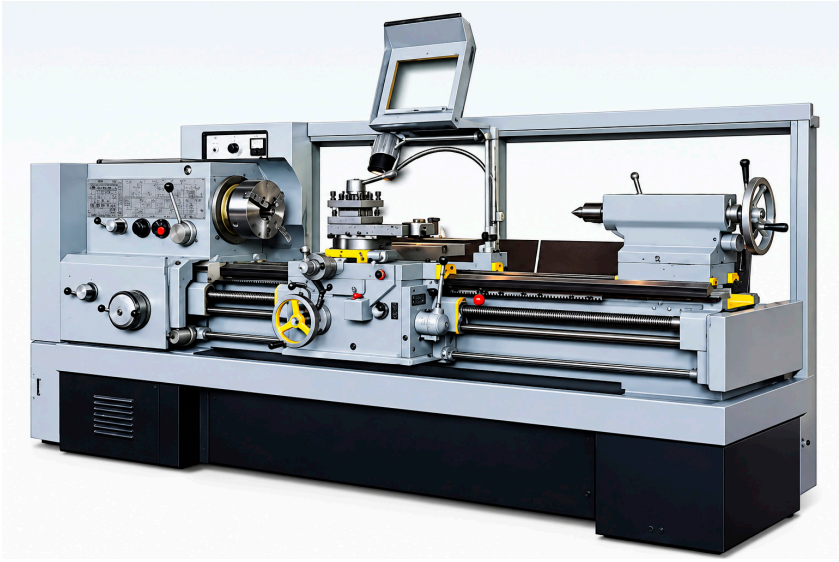


Figure 1. General view of the 1K62 screw-cutting lathe machine.

The machine has 23 speed ranges from 12.5 to 2000 rpm, providing wide machining capabilities [10]. Speed switching is carried out in the gearbox using interchangeable gears.

An asynchronous squirrel-cage induction motor (A61-4F2, LLC "PK Ruselprom", Moscow, Russia). (SCIM) is used, with a power rating of 10 kW and a rotational speed of 1450 rpm [13,14]. Regulation of spindle speed, as well as adjustment of longitudinal and transverse carriage movements, is performed through a gear-based speed gearbox system. To change spindle speeds and carriage feed rates, various control levers are used.

An additional asynchronous motor (AO32-4F2, LLC "PK Ruselprom", Moscow, Russia) with a power of 1 kW and a speed of 1410 rpm is used to achieve faster movement of the tool carriage.

The equipment is protected by fuses, which safeguard the network against short-term voltage surges. In case of prolonged overloads, thermal relays act as protection for the electric motors.

The spindle headstock is a sealed cast-iron housing, commonly referred to as the front or spindle headstock. Its main function is to transmit rotation to the workpiece, and it is located on the left side of the machine bed. The tool-holding assembly is mounted on this key component of the lathe.

The main elements of the spindle headstock include a stepped mechanical gearbox and a high-precision spindle shaft. The spindle is mounted on precision roller bearings [15].

As shown in the kinematic diagram (Figure 2), the rotational motion is transmitted from the primary electric motor through a V-belt drive to the input shaft of the gearbox. The complex arrangement of gears inside the headstock allows the spindle to achieve 23 distinct speed stages. This mechanical complexity highlights the necessity of implementing a frequency converter to simplify speed regulation electronically rather than mechanically.

The front bearing shaft receives rotational motion from a structure functioning as the main drive, which includes the following elements:

- A three-phase asynchronous electric motor, characterized by a rotational speed of n_m = 1450 rpm.

- S V-belt transmission: its transmission ratio is determined by the interaction of pulley parameters. The key feature is the ratio of pulley diameters: the motor pulley diameter (Ø 142 mm) and the gearbox pulley diameter (Ø 254 mm), with a ratio of 142/254.

Rotation from the input shaft—sometimes referred to as the friction shaft due to the presence of a pair of friction clutches in its structure—is transmitted through the gear train of the gearbox to the spindle. Further, from the spindle, the motion is transmitted to the feed drive mechanism.

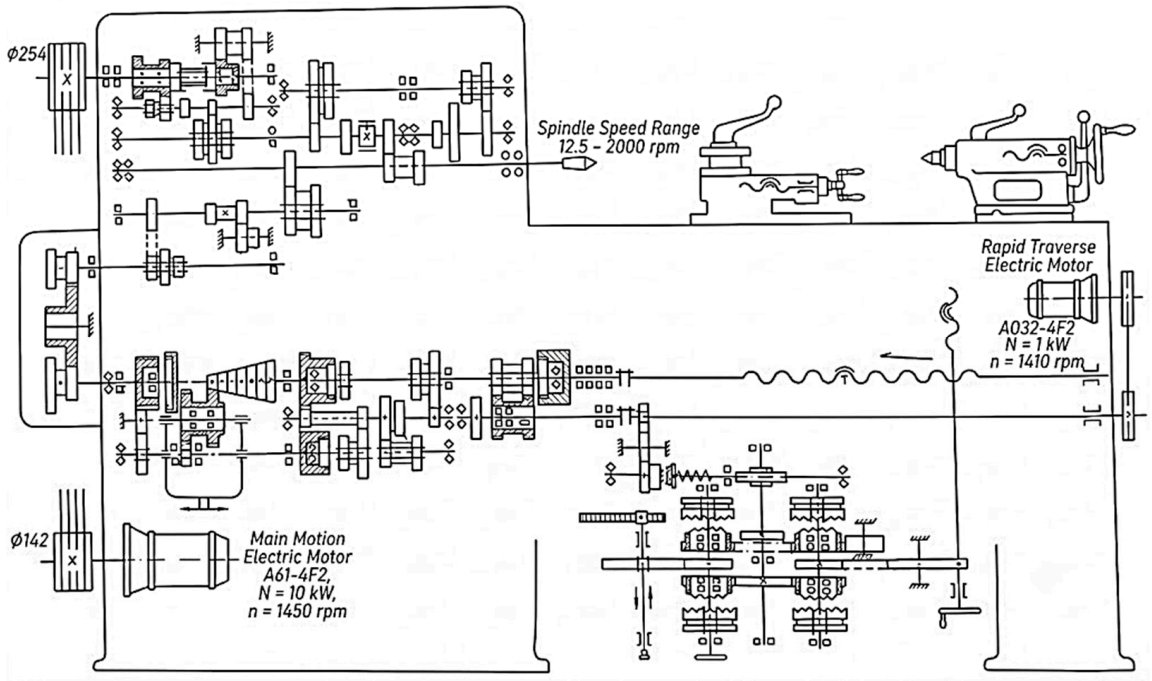


Figure 2. Kinematic diagram of the machine tool.

The current electric drive system used in the machine equipment has a limited number of spare components available in stock and lacks high reliability, which leads to frequent technical failures. The costs of repair work often result in downtime of the equipment. The implementation of a frequency converter with vector control in combination with an asynchronous motor will eliminate the above-mentioned disadvantages, reducing maintenance and repair time for the machine tool fleet.

2.2. Modernization Approach

The modernization of the electromechanical system of the 1K62 lathe-screw-cutting machine is aimed at improving energy efficiency [4], reliability, and control quality. The existing asynchronous motor A61-4F2 is replaced with a more efficient squirrel-cage induction motor—AIR M132M4 [13,14]—and a modern frequency converter Schneider Electric Altivar ATV71HD11N4 (Rueil-Malmaison, France) is also introduced [12].

As detailed in Table 1, the new AIR M132M4 motor (VEMZ, Vladimir, Russia) outperforms the legacy A61-4F2 motor in several key parameters. Specifically, the rated power is increased to 11 kW, and the efficiency is improved from 87.5% to 89%. Most importantly for the machining process, the nominal torque is increased from 65.86 Nm to 72 Nm, which is crucial for maintaining cutting stability under heavy loads. The selected motor has a higher efficiency of 89% and increased torque of 72 Nm, which ensures stable operation under variable loads. The frequency converter provides smooth speed regulation based on pulse-width modulation (PWM) [4,9], reducing the need for mechanical speed control.

Table 1. Comparison of characteristics of electric motors of the main drive system.

Characteristics	Type of Asynchronous Motor	
	A61-4F2	**AIR M132M4**
Rated power, kW	10	11
Rated rotational speed, rpm	1450	1460
Maximum rotational speed, rpm	1500	1500
Supply voltage Δ/Y, V	220/380	220/380
Rated current, A	19.7	22
Efficiency, %	87.5	89
Torque, Nm	65.86	72
Operating mode	Continuous S1	Continuous S1

A vector control method is applied, enabling independent control of torque and magnetic flux. This significantly improves dynamic performance, speed regulation accuracy, and system stability.

Overall, the modernization improves drive efficiency, reduces energy consumption, and lowers maintenance costs [4].

Table 2 clearly illustrates the superiority of the vector control system over the scalar control system. The vector approach provides a significantly wider control range (1:100 without a speed sensor compared to 1:40 in scalar control) and vastly superior control accuracy (0.2% vs. 2–3%). Moreover, vector control ensures a constant overload capacity across the entire speed range, which is a major limitation in scalar systems at low rotor speeds.

Table 2. Comparison of control systems.

Parameter	Vector Control System of Electric Drive		Scalar Control System of Electric Drive	
	Without Speed Sensor	**with Speed Sensor**	**Without Speed Sensor**	**with Speed Sensor**
Control accuracy	0.2%	0.02%	2–3%	0.03%
Control range	1:100	1:1000	1:40	1:40
Control method	Ψ_2 = const		$\frac{U}{f}$ = const	$\frac{U}{f}$ = const
Overload capacity	Constant over the entire speed range		Low at low rotor speeds	

2.3. Simulation in the Matlab Software

In the course of the work, a mathematical model of the electric drive with vector control was developed, as shown in Figure 3. The mathematical model includes: a squirrel-cage induction motor (SCIM), a frequency conversion device (known as an inverter), a power supply unit for the inverter, and a vector-type control system. This makes it possible to perform calculations aimed at determining the speed characteristics of the system in coordinate form, the frequency parameters of the inverter, and the structural forms of the components within the electric motor system.

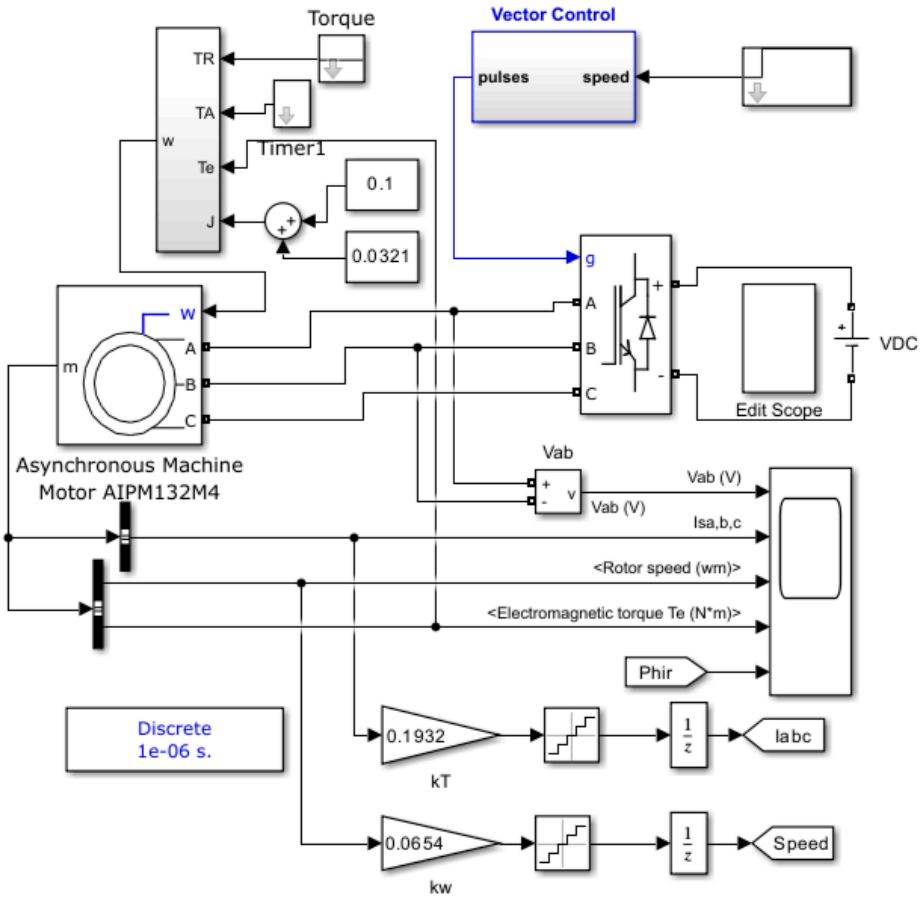


Figure 3. Mathematical model of the electric drive with vector control.

The central role in the structure of the electric drive (ED) is occupied by the vector control mechanism, a component of which is a subsystem shown in Figure 4.

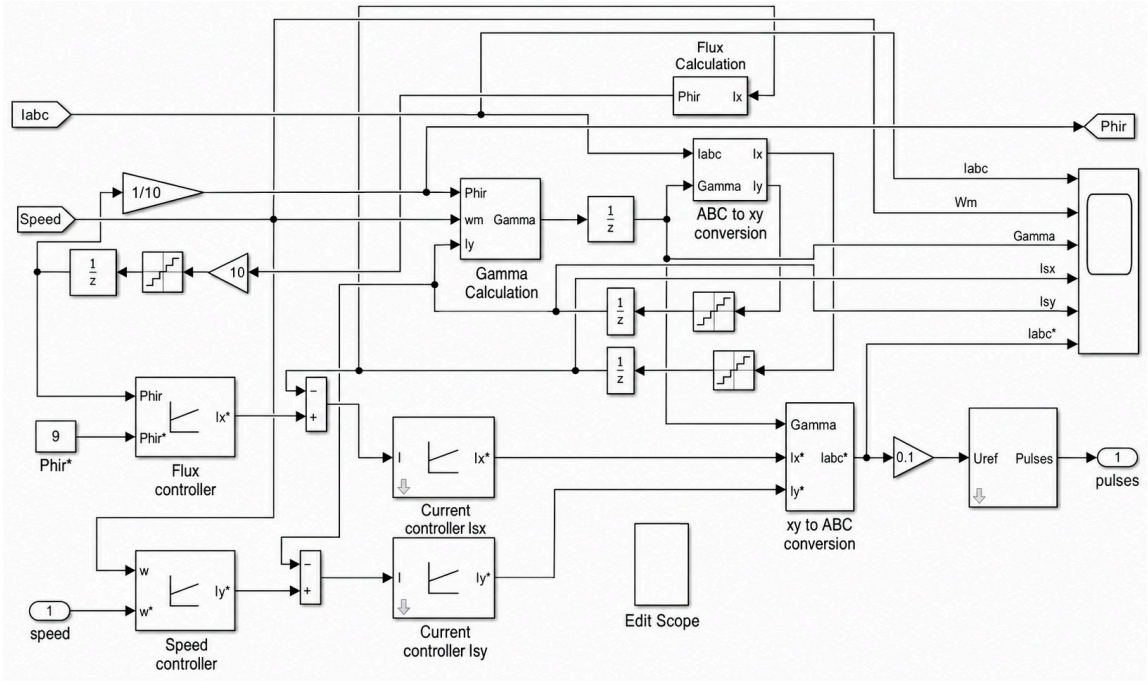


Figure 4. Control circuit model of the electric drive with vector control.

As illustrated in Figure 4, the control circuit accurately models the feedback loops necessary for vector control. In this model, the asterisk superscript (*) denotes the reference (setpoint) values for the respective control variables, distinguishing them from the measured or estimated actual feedback parameters. The subsystem continuously processes the stator currents and rotor speed to calculate the optimal voltage vectors. The integration of PI (Proportional–Integral) controllers within this circuit ensures that the actual torque and flux precisely track their reference values, thereby minimizing steady-state errors and improving transient response. Specifically, the flux controller receives the estimated rotor flux Phir and its reference value Phir* to generate the d-axis (magnetizing) reference current Ix*, while the speed controller compares the measured speed w (w_m) with the target reference speed w* to establish the q-axis (torque-producing) reference current Iy*.

The "Vector Control" branch within the SCIM system receives two measured parameters: the three-phase stator current and the rotor speed. This subsystem is used to determine the angular velocity in the ω_k coordinate system and the current angular position γ. In addition, the identification process is supported by the Gamma Calculation module.

For monitoring the processes in the electrical equipment, current regulators are used. They generate commands for the stator currents of the squirrel-cage induction motor (SCIM) in a two-phase orthogonal coordinate system, ensuring proper correlation with rotational motion dynamics. These inner-loop current controllers compare the generated reference currents (Ix*, Iy*) with the actual transformed components (Ix, Iy) to produce regulated control signals. The transformation of controller outputs into the stationary coordinate system is performed by the XY to ABC transformation block, which also converts the reference control signals into the three-phase reference currents (Iabc*) compatible with a three-phase network.

The task of generating three-phase power at the required operating frequency is carried out by the inverter (voltage source inverter, VSI). The power transistor switches forming the inverter perform current inversion and adjust the output voltage level. The switching of these transistors is controlled by a centrally configured control system.

A microprocessor unit processes motor parameter inputs and sets the required rotational speed and torque, generating and supplying the control pulses. The signal source, known as the Discrete PWM Generator1, serves as the control stage for the three transistor pairs, enabling regulation based on pulse-width modulation (PWM) principles. As a result, the operation of the analog-to-digital conversion system ensures the appearance of current and voltage in the windings of the SCIM.

The feedback signals obtained during processing, which represent current flow parameters, are directed to comparison circuits, where they are verified against the reference values set for the current controllers.

3. Result and Discussion

Figures 5 and 6 show the results of starting the electric drive with vector control. Overall, the drive satisfactorily handled the assigned task based on the output data.

When analyzing the operation of the electric drive under low rotational speed and minimal load conditions, it can be concluded that it is capable of performing its intended functions: it generates the required speed parameters and returns to the set rotational speed after load disturbances. Specifically, as observed in Figures 5 and 6, during the startup phase, the electromagnetic torque reaches its reference value rapidly with minimal overshoot, ensuring a smooth acceleration of the spindle. The stator currents stabilize quickly once the nominal speed is reached, which indicates the high dynamic performance and energy efficiency of the applied vector control system. Furthermore, during load disturbances, the system demonstrates robust behavior by restoring the reference rotational speed almost

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instantaneously without significant current oscillations. These factors critically contribute to the reduction in the starting current by avoiding the typical 5–7 times nominal current spikes seen in direct-on-line starts.

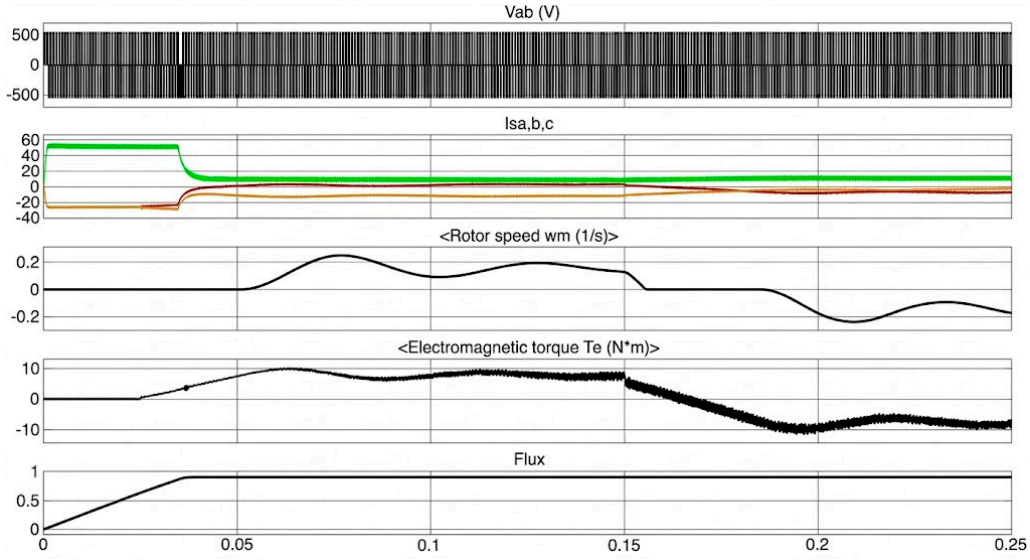


Figure 5. Starting and reversing of the electric drive with vector control: line voltage, V; stator winding currents, A; rotor speed w_m, 1/s; electromagnetic torque Te, N·m; rotor winding magnetic flux, Wb.

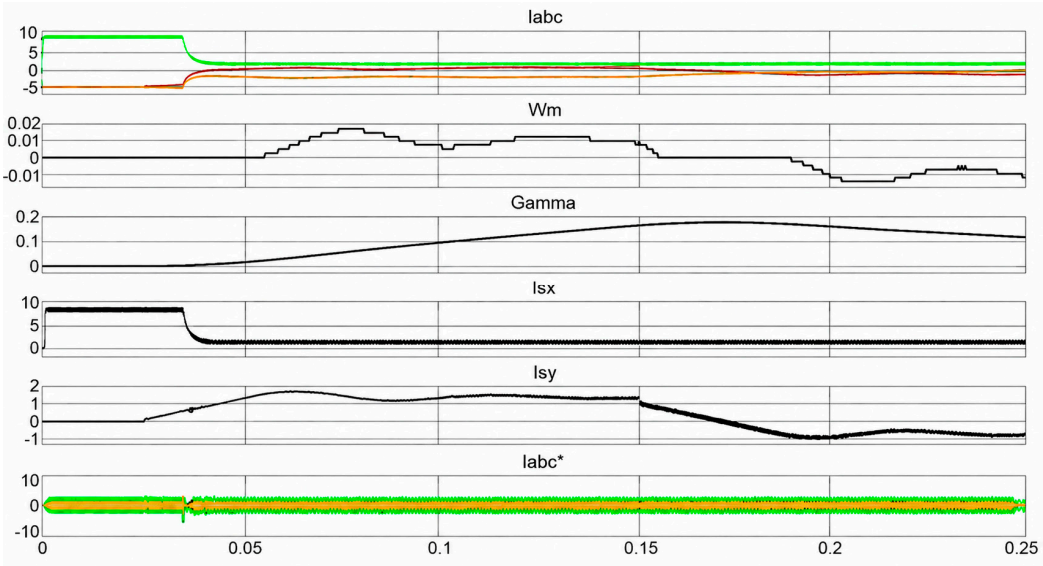


Figure 6. Starting and reversing of the electric drive with vector control: stator winding currents, A; reference rotational speed, w_m; coordinate rotation angle, γ; axis currents (Isx, Isy), A; reference stator winding currents (Iabc*), A.

Based on the study of engineering approaches in the synthesis of control systems for electric drives, it becomes evident that the vector control method is preferable in cases where high control accuracy and precise regulation of rotational speed and motor torque are required [16].

Line-to-line voltage (Vab)

- Observed values: High-frequency pulse-width modulated (PWM) switching pulses alternating between ±550.
- Dynamic behavior: The inverter supplies continuous PWM voltage patterns across the entire simulation duration. A brief switching transient/pause is noticeable around

$t \approx 0.038$ s, which marks the transition from the initial pre-fluxing phase to active motor torque generation.

Stator winding currents (Isa,b,c)

- Observed values: During the initial magnetization interval ($0 \leq t < 0.038$ s), one phase exhibits a constant DC level of +50 A while the remaining phases settle at −25 A.
- Dynamic behavior: Following the establishment of nominal flux ($t > 0.04$ s), the stator currents settle into their operating steady-state levels (approx. 10 A). At $t = 0.15$ s, the reversal command triggers an immediate shift in phase sequence and current amplitude to provide the required braking and reverse motoring torque.

Rotor speed (w_m)

- Observed values: Reaches a forward peak of approximately +0.21 1/s before stabilizing, and achieves −0.21 1/s in the reverse direction.
- Dynamic behavior: The rotor remains stationary ($w_m = 0$ 1/s) while the magnetic field develops. $t = 0.05$ s, forward acceleration begins, smoothly settling near the target forward speed. Upon receiving the reverse command at $t = 0.15$ s, the speed decreases monotonically, crosses zero without hesitation or instability around 0.165 s, and tracks the negative reference speed symmetrically.

Electromagnetic torque (Te)

- Observed values: Peaks +10 N· m during forward start-up and drops sharply to −11 N·m during dynamic braking/reversal.
- Dynamic behavior: Torque is held at zero (Te = 0 N· m for $t < 0.038$ s to prioritize rotor flux build-up. Once magnetized, positive torque is applied to accelerate the drive, settling around +8 N·m. When reversed at $t = 0.15$ s, the torque loop reacts instantaneously by applying a negative braking torque of −11 N·m before settling to steady reverse operation.

Rotor winding magnetic flux (Wb)

- Observed values: Linearly ramps up from 0 to a constant 0.9 Wb.
- Dynamic behavior: During the initial phase ($0 \leq t < 0.038$ s), the rotor flux is ramped to its rated value of 0.9 Wb. Throughout subsequent transient events—including sudden load acceleration, zero-crossing, and drive reversal—the flux linkage remains flat and undisturbed at 0.9 Wb, demonstrating decoupled flux and torque control under the vector control scheme.

Within modern electric drive control systems, a mathematical model of the electric motor is integrated. This allows the calculation of rotational speed and torque on the shaft. Only motor phase current sensors are used. The specific structure of the control system enables independent and fast variation in speed and torque on the shaft, minimizing the inertia of parameter regulation.

The use of vector control provides the following advantages [17,18]:

- High accuracy of speed regulation even without a speed sensor;
- Smooth, jerk-free motor rotation at low frequencies;
- Ability to maintain rated torque at zero speed (with a speed sensor);
- Fast response to load changes, with almost no speed fluctuations during sudden load variations;
- Improved operating mode of the electric motor, reducing losses due to heating and magnetization, thereby increasing motor efficiency.

The microprocessor-based control system of the frequency converter is a highly efficient unit that includes a set of additional modules. Its function is to control the switching

intervals of the transistors. This system ensures synchronized operation of the motor windings, which in turn maintains stable rotation of the asynchronous motor at the required speed level and provides the necessary torque development on its shaft.

It should be noted that the findings in the current manuscript are based on theoretical substantiation and mathematical modeling performed in the MATLAB (R2023b) environment [19,20]. While the simulation results demonstrate the clear advantages of the vector control system, physical experimental validation on an actual 1K62 machine tool constitutes a limitation of this proceeding paper. Therefore, physical experimental testing and empirical data collection are planned as the next critical step in our future research to fully validate the simulated efficiency gains.

4. Conclusions

The research demonstrated that the modernization of the 1K62 lathe machine electric drive system using a frequency converter and vector control method significantly improves the energy efficiency and operational performance of the machine tool. The proposed system ensures precise spindle speed regulation, stable torque at low rotational speeds, reduced starting current, and lower energy consumption.

The developed mathematical model confirmed the effectiveness of the vector control system during start-up, reverse operation, and load changes. The results showed stable operation of the asynchronous motor, improved dynamic characteristics, and fast response to load disturbances.

Compared with scalar control, the vector control method provides higher speed regulation accuracy, smoother operation at low frequencies, reduced vibration, and improved machining stability. In addition, the use of the AIR M132M4 motor and Schneider Electric Altivar ATV71HD11N4 frequency converter increased the overall efficiency and reliability of the electric drive system.

Thus, the implementation of vector-controlled electric drives in metalworking machine tools is an effective solution for reducing energy losses, improving machining quality, increasing equipment service life, and optimizing industrial production processes.

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