

Voltage/Frequency Speed Control of CNC Machining Center's Spindles Retrofitted by Delta ASD-S 4.5kW High Performance VFD

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Abstract

CNC machine tools include an essential element known as the spindle, which must operate at high speeds and sustain a consistent velocity even when torque fluctuates during use. Generally, this spindle is powered by an alternating current (AC) electric motor that serves as the torque source, facilitating the required rotational speed for various cutting tasks. This article aims to explore a method for controlling speed through variable frequency voltage control (VVVF or V/f), specifically for CNC machine spindles. Initially, a model of rotational speed is created based on Newton's second law, taking into account the interactions among the AC motor, gear system, and rotating spindle. Next, a mathematical representation of the induction motor is developed in the d-q axis framework to assist in crafting the speed controller. Subsequently, a closed-loop speed control mechanism is initiated; this process begins with defining a reference speed and then processing these values through an electrical circuit to produce the necessary voltage and frequency before supplying them to the AC motor model. System modeling and performance assessment concerning speed control and dynamic response under torque load were conducted using MATLAB/Simulink. The V/f control system was established with a high-efficiency Delta ASD-S 4.5kW Variable Frequency Drive (VFD) sourced from Delta Electronic Inc. in Taiwan, aimed at performing speed control regulation on the spindles mounted on the CNC Machining Center model ARCO A-56 APC. To manipulate the reference and system response, a PI controller was utilized in control loop.

Keywords : Induction Motors, Variable Voltage Variable Frequency (VVVF), MATLAB Simulink, Motor Control.

Introduction

A high-speed machining system comprises several key components, including the machine tool, spindle, and computer numerical control (CNC) system. Spindle is an important part. It is normally applied by an Induction motors (IM), also known as asynchronous machines, are often preferred over Direct Current (DC) motors due to their low maintenance costs, absence of arcing during operation, and economic efficiency. These motors find various applications in industry; while single-phase induction machines are typically produced for low power applications, three-phase induction machines are predominantly employed in industrial and factory settings. Despite the numerous advantages they offer over DC motors, induction machines present a complex structure and exhibit non-linear characteristics that pose substantial challenges in their control. Efficiency in induction machines can be significantly enhanced through speed and torque controls. Several control methods, such as scalar voltage control, scalar resistance control, and vector control, have been developed for this purpose. However, their implementation often tends to be complex and associated with high costs [1]. Then, this paper focuses on implementing speed control in induction machines by Variable Voltage Variable Frequency (VVF or V/f Control). These methods will be examined in Simulink to evaluate their performance characteristics and operational efficiencies. There are various control techniques for induction motors aimed at achieving consistent speed characteristics. Notable methods include scalar control and vector control, among others [2-5]. The widely-used V/F method for operating induction motors has been established for many years [6]. This approach utilizes the stator flux and torque discrepancies to produce the necessary stator voltage and frequency [7 - 10]. To enhance reliability, flexibility, and ease of managing errors—thereby ensuring constant speed performance in induction motor drives—microcontrollers are increasingly employed.

In this research, a model for a three-phase induction motor along with a spindle rotation model was created using the principles of mathematical modeling. The motor's speed was regulated employing the Variable Voltage Variable Frequency Technique. Control parameters were validated using MATLAB/Simulink, and the results are presented to illustrate the effectiveness of the control system. Finally, the ASD-S High Performance VFD produced by Delta Electronics Inc. Taiwan was selected to regulate the spindle speed of the CNC, replacing the previous unit that was damaged due to prolonged use in a challenging environment.

Preliminaries

1. Dynamical model of Spindles

For the high-speed machining operation, the spindle system featuring an AC motor circuit is depicted in Figure 1. This addresses the dynamic interactions between the AC motor, gears, and spindle movements.

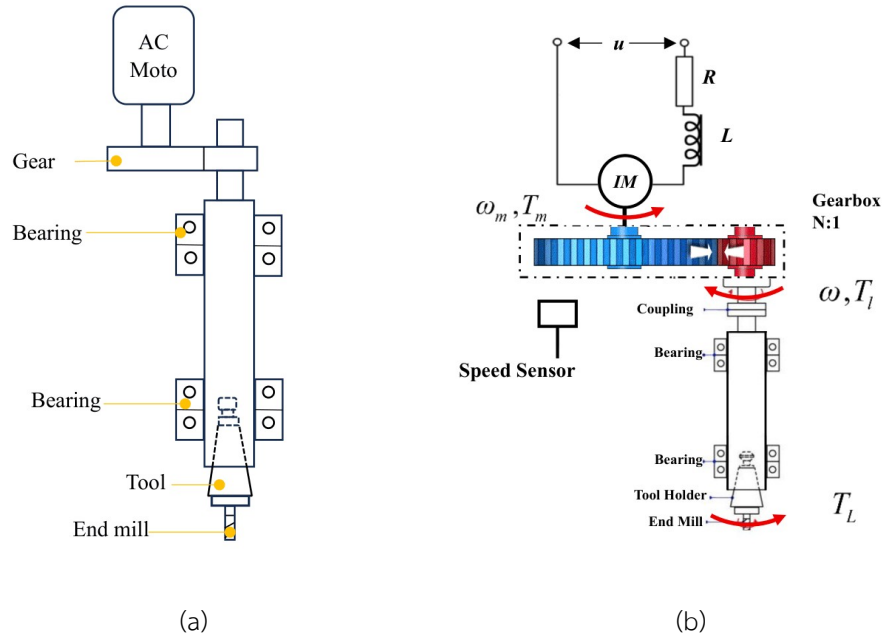


Figure 1 (a) CNC's Spindle ; (b) Free body diagram

The rotational dynamics of motor are described as

$$J_m \dot{\omega}_m = T_e - B_m \omega_m - T_m . \quad (1)$$

Defining $\dot{\theta} = \omega$, we can write the rotational dynamic of Spindle as

$$J_s \dot{\omega} = T_l - B_s \omega - T_L \quad (2)$$

where T_m denotes the input torques associated with the gear set, T_l is the output torques produced by the gear set, and T_L is torque load. The relation between both torques can be described as

$$T_l(t) = N T_m(t) \quad (3)$$

where N is the transmission ration of gear set. Substituting the relation $\omega_m = N\omega$ into (1) - (2), and then eliminating T_m , dynamic model can be simplified as follows:

$$\dot{\theta} = \omega \quad (4)$$

$$J_{eq} \dot{\omega} = Nu - B_{eq} \omega + T_d \quad (5)$$

where $B_{eq} = B_s + B_m N^2$, $J_{eq} = J_s + J_m N^2$ and $T_d = \delta - T_L$ are the equivalent viscous damping coefficient , the equivalent total inertia of spindle system and a group of uncertainties, respectively.

2. Induction Motor

In our design, we incorporate a squirrel-cage asynchronous induction motor. This type of induction motor is favored for its durability, straightforwardness, and affordability. In this motor, the magnetic field generated by the stator induces an electric current in the rotor bars, resulting in torque that causes the rotor to rotate. Its functioning is based on the principle of electromagnetic induction, where the rotor speed is

consistently slightly lower than that of the stator's magnetic field to ensure proper induction. The dynamic equivalent circuit or d-q analysis and simulation are commonly utilized methods based on a rotating reference frame, as illustrated in Figure 2.

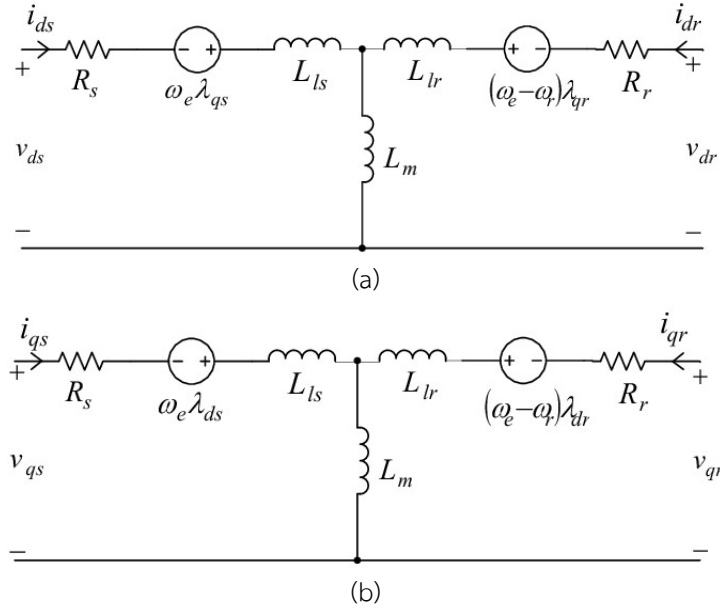


Figure 2 (a) d-Axis equivalent circuit; (b) q-Axis equivalent circuit.

The analysis of the stator side necessitates a study of the differential equations associated with the circuits shown in Figure 2. Voltage across the stator loop in d-q axis can be written as

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs} , \quad (6)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_e \lambda_{ds} . \quad (7)$$

Conversely, the rotor side is represented as follows:

$$v_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r) \lambda_{qr} = 0 , \quad (8)$$

$$v_{qr} = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_e - \omega_r) \lambda_{dr} = 0 . \quad (9)$$

Assuming that the examined induction motor is a squirrel cage type, this results in the voltage in equations (8) and (9) being equal to zero. The expressions for the flux linkages can be represented as follows:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} , \quad (10)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} , \quad (11)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} , \quad (12)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} . \quad (13)$$

In these equations, L_s denotes the self-inductance of the stator, L_r signifies the self-inductance of the rotor, and L_m represents the mutual-inductance. The parameter L_{ls} denotes the stator-leakage inductance, while L_{lr} represents the rotor-leakage inductance. The self-inductances can be represented as follows:

$$L_s = L_m + L_{ls}, \quad (14)$$

$$L_r = L_m + L_{lr}. \quad (15)$$

The speed at which rotation occurs is referred to as synchronous speed, defined by the equation:

$$\omega_s = \frac{120f}{P} \quad (16)$$

where f represents the supply frequency and P indicates the number of poles. The difference between the synchronous speed ω_s (or ω_m^* as a set point) and actual speed ω_m of the rotor is called as slip as seen below:

$$s = \frac{\omega_s - \omega_m}{\omega_s}. \quad (17)$$

The summation of notation is illustrated in Table 1.

3. The principles of V/f Control

As mentioned in the previous chapter, when we focus solely on the stator flux reference frame, the governing equation for the stator circuit is:

$$V_{dqs} = R_s i_{dqs} + \frac{d\lambda_{dqs}}{dt} + j\omega_e \lambda_{dqs}. \quad (18)$$

In steady-state, equation (18) can be simply represented by:

$$V_{dqs} = R_s i_{dqs} + j\omega_e \lambda_{dqs}. \quad (19)$$

If we disregard the voltage drop across the stator resistance and focus solely on its magnitude:

$$\lambda_{dqs} \approx \frac{V_{dqs}}{\omega_e} \quad (20)$$

Under these circumstances, the machine's speed is directly proportional to the stator voltage. To run the machine at standard conditions, the stator flux needs to be at its nominal level

$$\lambda_{dqs}^* = \lambda_{dqs} \approx \frac{\sqrt{2} V_{sn}}{\omega_{en}} \quad (21)$$

, where V_{sn} represents the nominal RMS phase voltage and ω_{en} denotes the nominal frequency. Then, based on equations (20) and (21), the speed reference may be transformed into a voltage reference as

$$V_{dqs}^* \approx \lambda_{dqs}^* \omega_e^* = \frac{\sqrt{2} V_{sn}}{\omega_{en}} \omega_e^*. \quad (22)$$

V/f profile could be programed as a look up table or just a simple linear function indicated in Figure 3.

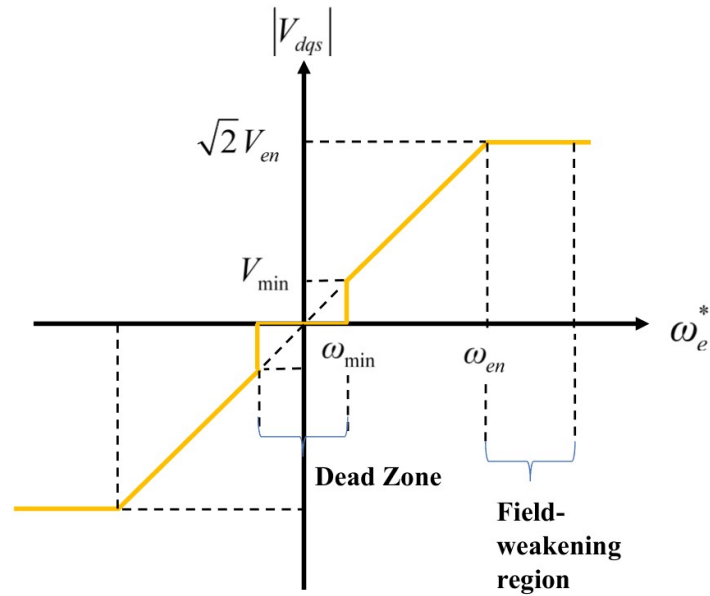


Figure 3 V/f Profile.

4. Closed-loop version of V/f control

V/f control relates the ratio of voltage amplitude to frequency. In a closed-loop configuration, a PI controller can proficiently compensate for this slip speed and can be manually fine-tuned while the motor is in operation. The complete control block diagram is illustrated in Figure 4.

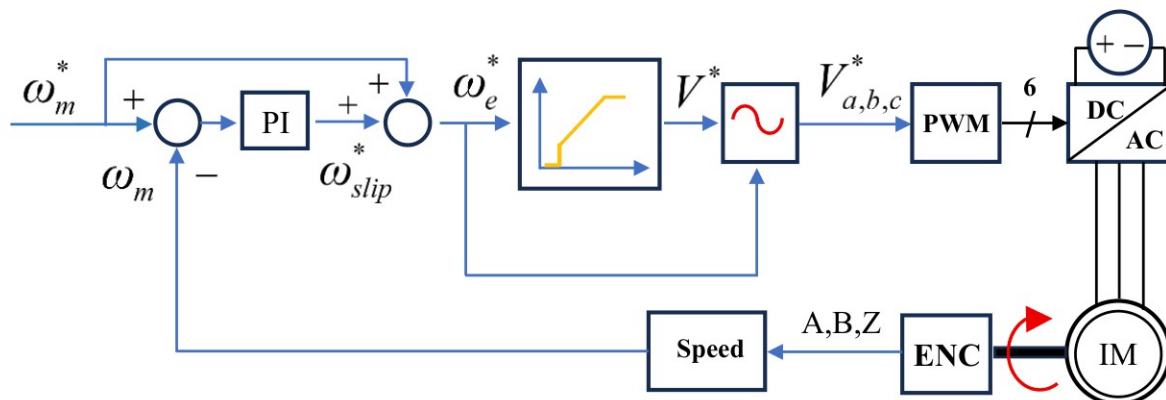


Figure 4 Block diagram of closed-loop V/f control.

1. Speed tracking Simulation

However, this gain must not be excessively high, as doing so could negatively impact control stability. In the situation outlined, although the actual slip undergoes abrupt changes with load variations, the estimated slip changes gradually due to restrictions set by the dynamics of the PI controller.

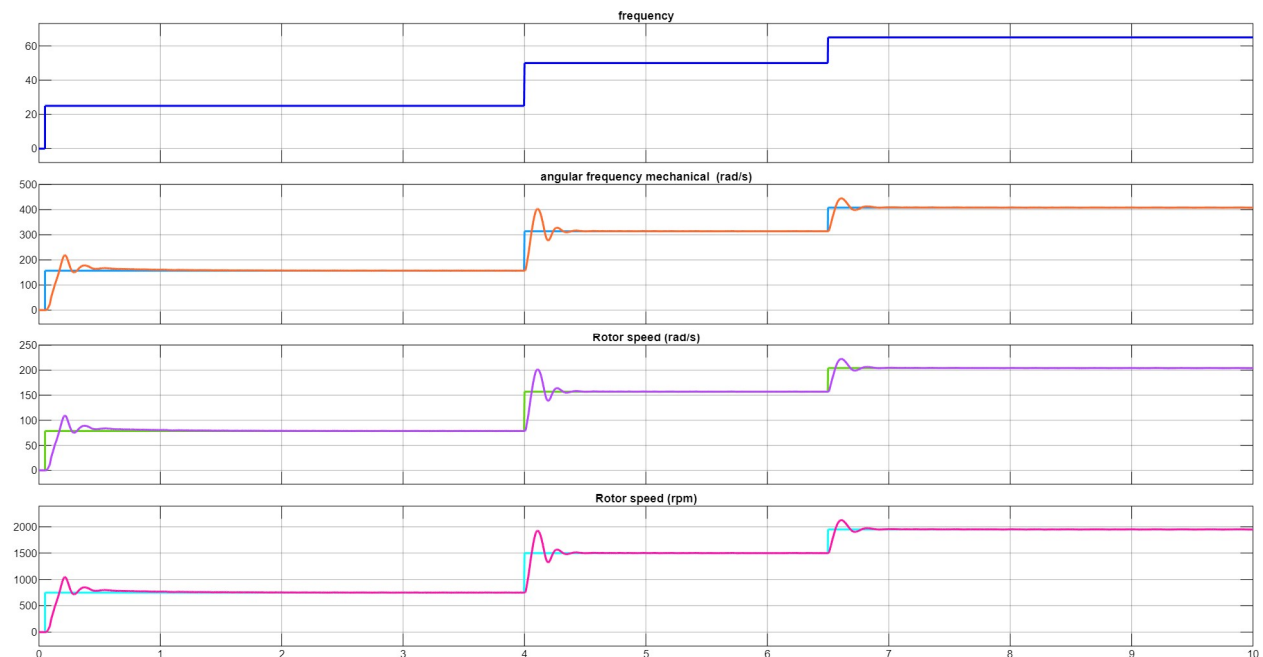


Figure 6 Simulation results.

2. Experiment

The experiment utilized a ten-year-old CNC Machining Center no longer used, specifically the ARCO A-56 APC model produced in Taiwan, which has been retrofitted as illustrated in Figure 7. In this process, we completely overhauled all mechanical components and replaced every electrical device, including the CNC Controller, Spindle Motor, Spindle Drive, Servo Motors, Servo Drives, and other electrical devices within the control cabinet. This paper will concentrate exclusively on the Spindle Systems, which comprise an AC Motor integrated with an ABZ 1024 pulses per revolution (ppr) incremental encoder, gear mechanism, and spindle drive. Despite the high-performance capabilities of this drive manufactured by Delta Electronics Inc., which can operate under either V/f control or Vector Control modes, our focus will be on examining the V/f algorithm. Experiments were conducted using identical motor and controller parameters as outlined in Table 1. The step speed was initially set at 160 rad/s (approximately 1,600 rpm); after three seconds, a command was issued to reduce the speed to 120 rad/s. The outcomes both speed response and torque were captured via ASD-S Drive software and are presented in Figure 8. Figure 9 illustrates the currents flowing through the stator, with an average current value of approximately 25 Amperes, while the peak current can reach about 50 Amperes. Figure 10 presents the voltage per phase, which is around 600 Volts, slightly exceeding the motor's rated voltage. Figure 11 depicts the error values during operation, showing that the difference between the speed reference

and the actual speed response ranges from 0 to 25%. Ideally, we aim for this error to be as close to zero as possible throughout operation; however, in practice, it fluctuates continuously under torque load variation. Additionally, Figure 12 expresses data related to DC-Link voltage. This voltage is utilized to generate the sine wave supplied to the induction motor. The stability of the DC-Link is crucial for ensuring consistent power delivery to the motor. During experiments, the DC-Link voltage consistently measures around 650 VDC.

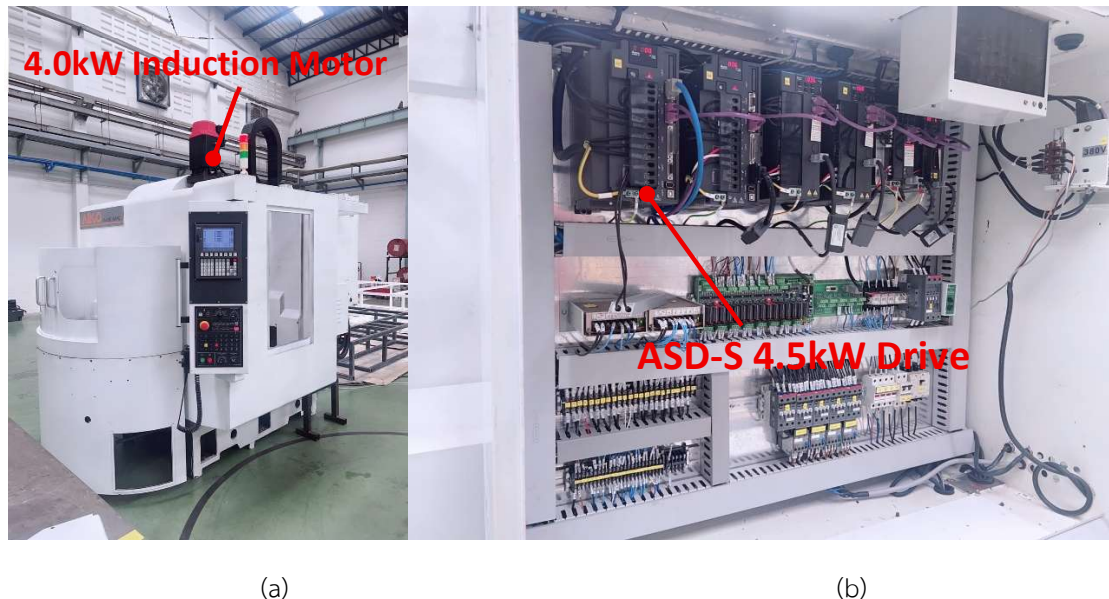


Figure 7 CNC Machining Center with (a) 4.0kW Induction Motor; (b) ASD-S 4.5kW VFD.

Conclusions

This study conducted a control techniques applicable to induction motors, specifically focusing on Variable Voltage Variable Frequency (VVVF) method. The effectiveness of these strategies concerning speed regulation and dynamic response was evaluated through simulations on the MATLAB/Simulink platform. The findings revealed several limitations associated with the V/f approach, including a potentially sluggish response time and significant overshoot, along with its inability to address steady-state errors. Despite these shortcomings, the V/f method remains one of the most widely utilized techniques for speed control in industrial settings. Additionally, this research included experiments involving a 4.0 kW induction motor powered by a high-performance variable frequency drive (VFD) produced by Delta Electronics Inc., Taiwan, which yielded satisfactory results. For future investigations, it is noted that while the VVVF control method offers a straightforward and cost-effective solution for managing AC motor speed, it is also hindered by specific limitations. Consequently, alternative strategies such as Field-Oriented Control (FOC) have emerged as sophisticated options for AC motor drives, demonstrating enhanced responsiveness and improved torque regulation capabilities.

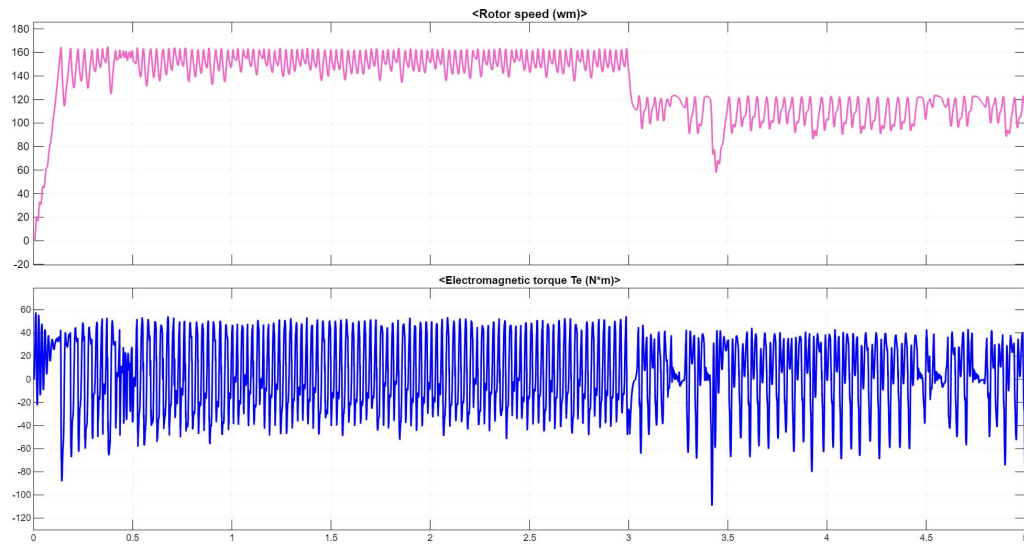


Figure 8 Speed response at 160 rad/s and 120 rad/s and Torque.

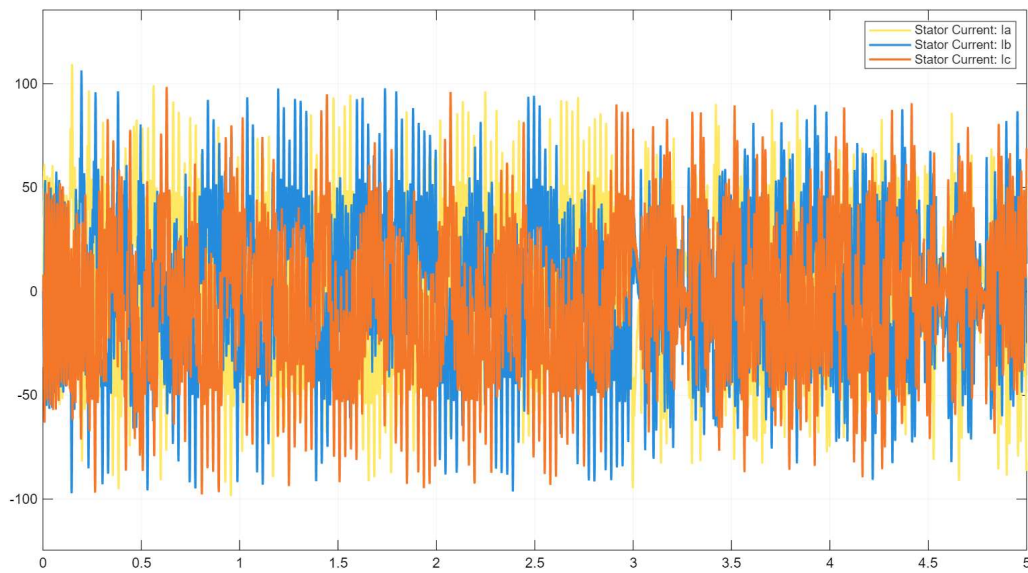


Figure 9 Stator Current.

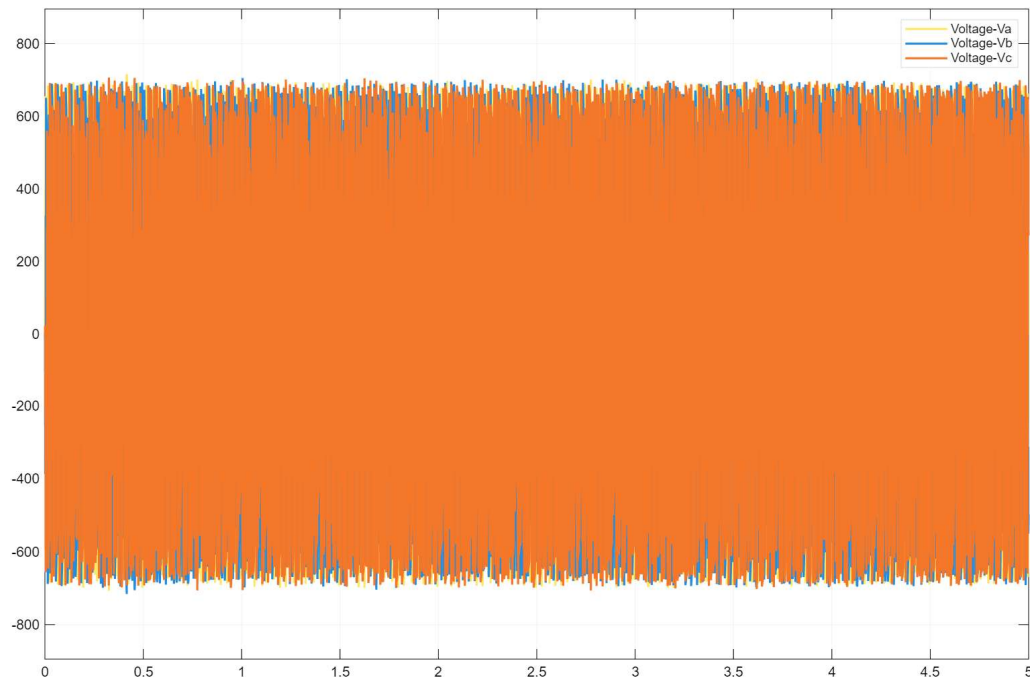


Figure 10 Phase Voltage.

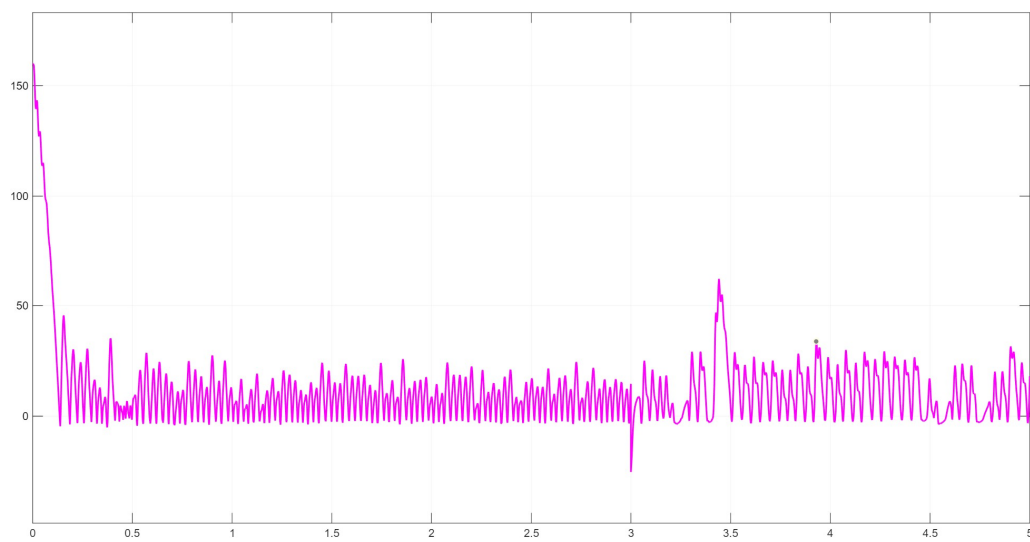


Figure 11 Error during operation.

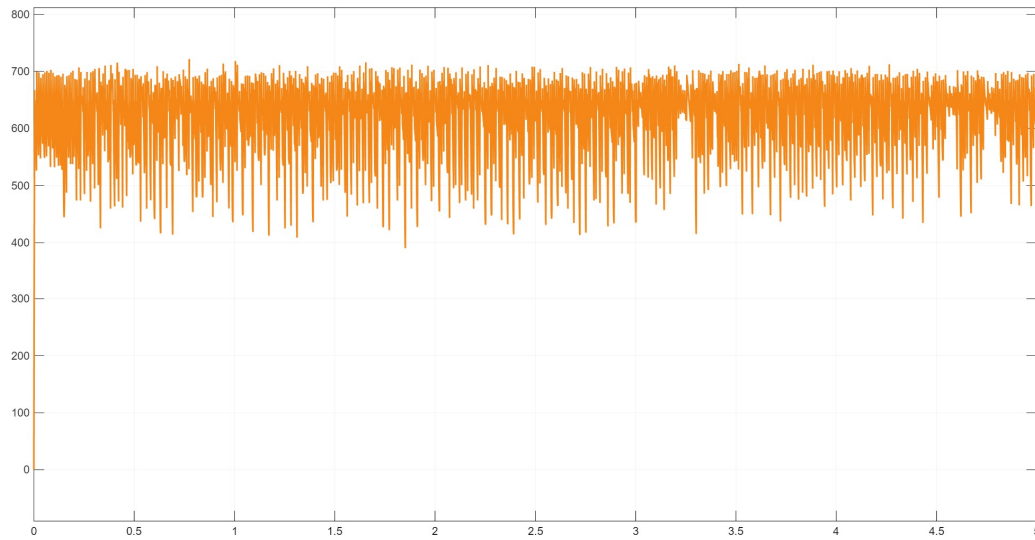


Figure 12 DC-link voltage.

Table 1. Induction Motor, Gear and PI controller parameters

Notation	Meaning	Value
k_p, k_i	PI Gains	0.12 , 0.3268
$P_n(W)$	Nominal Power	3,730
$V_n(rms)$	Voltage RMS	530
f_n	Nominal frequency	50
$R_s(ohm)$	Stator resistance	1.115
$L_{ls}(H)$	Stator-leakage inductance	0.005974
$R_r(rms)$	Rotor resistance	1.083
$L_{lr}(H)$	Rotor-leakage inductance	0.005974
$L_m(H)$	Mutual-inductance	0.2037
$J_m(kg.m^2)$	Inertia of motor	0.02
$B_m(N.m.s)$	Friction Coefficient of motor	0.005752
P_r	Pole pairs	2
$J_m(kg.m^2)$	Inertia of spindle	0.1
$B_s(N.m.s)$	Friction Coefficient of spindle	0.008
N	Gear ratio	1:1.92

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