Open-Loop Performance Analysis of Induction Motors under V/f Speed Control

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ABSTRACT

This study aims to analyze the performance of a three-phase induction motor with a speed control system based on the Volt per Hertz (V/f) method in an open-loop configuration, with a primary focus on reducing torque drop during low-frequency operation. The simulation was carried out using MATLAB/Simulink, where the model consists of an SPWM-based three-phase inverter, a standard Simulink induction motor, and an external mechanical load. The V/f method was applied to maintain constant stator flux by keeping the voltage-to-frequency ratio fixed (approximately 7.6 V/Hz). The input frequency was varied from 10 Hz to 50 Hz, both under no-load and loaded conditions. The observed performance parameters included rotor speed, electromagnetic torque, stator current, and motor slip.

The simulation results show that the system can produce a linear relationship between frequency and rotor speed with low slip (<5%) under no-load conditions. However, under load conditions, there is a speed drop of around 4–5% that cannot be compensated due to the absence of a feedback system. The initial electromagnetic torque demonstrates a fast response with an overshoot of up to 150 Nm before stabilizing in the range of 100–120 Nm. The rotor speed reaches a steady-state condition in approximately 0.2 seconds, indicating good dynamic response.

In conclusion, the open-loop V/f control system is effective and sufficiently efficient for light industrial applications that do not require high precision, such as fans and pumps. However, for applications that demand greater stability and dynamic response, further development toward a closed-loop system or sensor-based adaptive control is recommended to enhance control accuracy, energy efficiency, and system capability in responding to dynamic loads

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1. INTRODUCTION

The Induction motors are among the most widely used types of electric motors in modern industrial drive systems. Their popularity is based on several technical advantages, such as simple structure, low maintenance cost, high reliability of up to 91%, and good operational capability under various load conditions[1]. Compared to similar motors such as synchronous motors or DC motors, three-phase induction motors are generally more resistant to external disturbances and more economical in application. Consequently, induction motors are commonly found in pump drives, fans, conveyors, compressors, and variable-speed production machinery in manufacturing and industrial automation[2].

In practice, many industrial processes require flexible motor speed regulation to adapt dynamically to process demands. Speed control plays a crucial role in improving energy efficiency, maintaining product quality, and extending the service life of mechanical components driven by the motor. Operating the motor continuously at its nominal speed is not always efficient, especially when the system does not require full speed at all times. Therefore, a reliable, cost-effective, and easily implemented speed control method is needed. One widely used approach for controlling the speed of induction motors is the voltage-to-frequency control technique, known as the V/f Control (Volt per Hertz Control) method[3].

The V/f technique is a method of controlling induction motor speed by maintaining a constant ratio between the supply voltage and the input frequency. This ratio is important for keeping the magnetic flux in the machine stable so that the motor operates under optimal conditions. In induction motors, magnetic flux is directly proportional to voltage and inversely proportional to frequency. If the V/f ratio changes significantly, magnetic saturation or torque reduction may occur, which can affect the overall performance and efficiency of the system. By maintaining a constant V/f ratio, the motor can operate at various speeds while retaining good torque characteristics and efficiency over a certain speed range[3][4].

One of the main advantages of the V/f technique is its simplicity in implementation. This system does not require a speed feedback sensor, which is why it is referred to as an open-loop system. Inverters or variable frequency drives (VFDs) that implement this method simply adjust the output frequency and voltage based on the speed reference provided by the operator or control system. As a result, this method is more economical compared to closed-loop control systems that use speed sensors or encoders [5]. Open-loop V/f-based systems are widely applied in applications that do not require high speed precision, such as pumps, blowers, or industrial fans[5][6].

However, open-loop systems also have certain limitations. One major drawback is their inability to handle load changes in real time. Without feedback, the system cannot directly adjust output voltage and frequency based on the motor's actual condition. This may result in speed deviations when load fluctuations occur, especially in applications requiring fast dynamic response or high speed precision. In addition, at very low speeds, motor torque tends to decrease due to the minimum voltage limitations that can be supplied by the inverter, reducing system performance. Therefore, it is important to understand the characteristics of open-loop V/f systems to ensure they are applied effectively within their operational constraints[7].

In this context, research and implementation of induction motor speed control systems based on the V/f technique in open-loop configurations become relevant and important topics for further investigation. This article aims to explore the working principle of the V/f technique, design an open-loop induction motor speed control system, and analyze system performance through experimental testing. The main focus of this article is to identify the extent to which the V/f technique can provide stable and efficient speed control in systems without feedback. Accordingly, the results of this study are expected to provide practical insights for the development of simple yet efficient industrial drive systems, as well as serve as a preliminary reference for transitioning to closed-loop control systems when higher precision and adaptability are required.

Furthermore, this article also presents an overview of the hardware configuration used, including a three-phase induction motor, variable frequency inverter, and a microcontroller- or PLC-based control interface. Testing is conducted to evaluate speed response to variations in input frequency under both constant load and varying load conditions. The results obtained are compared with theoretical calculations and ideal performance analysis to provide a comprehensive understanding of the strengths and limitations of the open-loop V/f system. Through this approach, it is expected that readers both industry practitioners and academics can benefit from the research findings as a basis for implementing speed control systems tailored to their specific application needs.

2. Literature Review

2.1. Operating Principle of Induction Motors

The three-phase squirrel-cage induction motor is an AC machine that operates based on the principle of electromagnetic induction. When a three-phase AC voltage is applied to the stator, it produces a rotating magnetic flux that cuts through the rotor, inducing current in the rotor conductors. This induced current generates an electromagnetic force (torque) that causes the rotor to rotate synchronously with the stator's rotating field, minus the slip. Slip (s) is defined as the difference between the synchronous speed (ωs) and the mechanical rotor speed (ωm)[8].

Torque (T) in an induction motor is generally related to slip and rotor current, while motor efficiency is highly dependent on torque and stator–rotor resistive losses[9]. Baghel et al. presented an analysis of torque and efficiency in real operating conditions under load, demonstrating how to measure motor impedance and slip without removing the load to determine the actual efficiency [10].

2.2. Theoretical Basis of Speed Control: V/f Control

Induction motor speed control using the V/f (Volt per Hertz) or Constant Volts–Hertz (CVH) technique works on the principle of maintaining a constant ratio of voltage (V) to frequency (f) so that the stator magnetic flux remains constant. Consequently, the produced torque remains stable when the frequency (speed reference) changes. The V/f ratio is expressed as:

$$V/f = \text{konstan} \tag{1}$$

In practice, this ratio can be modified as a linear or quadratic function to compensate for stator winding resistance losses at low frequencies or to maintain maximum torque at high frequencies. Hua et al. compared linear and quadratic V/f control to analyze their effect on motor torque characteristics and recommended a minimum voltage value for stator resistance compensation to maintain performance at low frequencies [11].

2.3. Open-Loop vs Closed-Loop Control Systems

An open-loop control system does not use a feedback sensor; the inverter only regulates voltage and frequency based on the input reference. This approach is suitable for applications with nearly constant loads and gradual speed changes and is referred to as scalar control[12]. Its advantages include low cost and relatively simple implementation. In contrast, a closed-loop V/f system uses a speed sensor (encoder/tacho) and a PI controller. The error between the reference and the actual speed is corrected in real time, enabling the motor to operate with higher accuracy, particularly under varying load conditions or dynamic torque demands[13].

2.4. Peran SPWM Inverter dalam Sistem V/f

A sinusoidal pulse-width modulation (SPWM)-based inverter is a modulation technique in which a sinusoidal reference signal is compared with a triangular carrier wave. The SPWM output produces a fundamental voltage equal to the reference frequency, with amplitude depending on the modulation index. SPWM is widely used in variable frequency drives (VFDs) to generate three-phase AC signals that closely resemble sinusoidal waveform[14]. Heba Abdul-Jaleel Al-Asady reported that a microcontroller-based SPWM modulator in scalar V/f open-loop control produces near-sinusoidal waveforms, with the modulation index adjustable linearly with frequency (0–55 Hz), resulting in precise and stable motor speed[15]. Zhao et al. compared SPWM and SVPWM in scalar V/f open-loop control, finding that SVPWM provides faster speed response, lower total harmonic distortion (THD) (~9%) compared to SPWM (~17%), and better stability against torque load fluctuations[16]. Nevertheless, SPWM remains a preferred choice due to its simplicity and lower implementation cost.

2.5. Previous Studies on Open-Loop V/f Technique

Several national studies have implemented and investigated the open-loop V/f technique under various application conditions. Haryanto (2011) reported the design of a single-phase inverter module with constant V/f control, successfully regulating speed from 262 rpm (10 Hz) to 1,826 rpm (60 Hz) under no load, with a constant V/f ratio of about 2.34, and a linear speed change of approximately 31.2 rpm/Hz[17]. Zakariya (2020) focused on the development of single-phase SPWM using a microcontroller, achieving precise sinusoidal waveforms and effective open-loop V/f implementation for specific slip speeds [18]. Furthermore, evaluations of varying V/f profiles (linear vs quadratic and minimum voltage adjustment) on the torque characteristics of three-phase induction motors determined that the appropriate ratio can maintain maximum torque and efficiency under changing loads, while reducing torque drop at low frequencies [19].

2. METHOD

This study was conducted through simulation using MATLAB/Simulink to analyze the performance of a three-phase induction motor with voltage and frequency regulation based on the V/f (Volt per Hertz) method. The main focus is on the relationship between supply frequency, rotor speed, electromagnetic torque, and slip under both no-load and load conditions.

1. Simulation Model Design

The simulation model consists of:

- A three-phase inverter based on SPWM (Sinusoidal Pulse Width Modulation)
- A three-phase induction motor (standard Simulink model)
- Mechanical load configuration in the form of external load torque
- Signal measurement and monitoring unit

Sinusoidal PWM generates six control signals (S1–S6) to operate the inverter switches. The inverter's output voltage is supplied to the induction motor as three-phase phase voltages (R, Y, B)

2. Equations Used

a) Voltage–Frequency Relationship (V/f. To maintain constant stator flux, the following principle is applied :

$\frac{V}{f} = \text{constant}$; Where; V = Motor supply voltage (volts); f = Supply frequency (Hz)

b) Synchronous Speed of the Induction Motor:

$$N_s = \frac{120 \cdot f}{p} \quad (2)$$

Where: N_s = Synchronous speed (rpm); f = Supply frequency (Hz); p = Number of motor poles;
c) Motor Slip;

$$S = \frac{N_s - N_r}{N_s} \times 100\% \quad (3)$$

Dengan: N_r = Actual rotor speed (rpm)
d) Electromagnetic Torque of the Induction Motor (Te)

$$T_e = \frac{3}{\omega_s} \cdot \frac{r_{r'}}{s} \cdot \left(\frac{V^2}{(r_s + \frac{r_{r'}}{s})^2 + (x_s + x_{r'})^2} \right) \quad (4)$$

where: T_e = Electromagnetic torque (Nm); ω_s = Synchronous angular speed (rad/s); $r_{r'}$ = Rotor resistance referred to the stato; r_s, x_s = Stator resistance and reactance; $x_{r'}$ = Rotor reactance referred to the stator; s = Slip

3. Frequency and Load Variation

The input frequency is varied at five points: 10 Hz, 20 Hz, 30 Hz, 40 Hz, and 50 Hz. For each frequency point, simulations are conducted under two conditions: No-load (load torque = 0 Nm),Loaded (constant load torque, e.g., 2 Nm)

4. Observation and Data Acquisition

The parameters observed and recorded include:Actual rotor speed (rpm); Electromagnetic torque (Nm);Slip (%)Stator and rotor currents. Simulation results are compiled into numerical tables and compared between no-load and loaded conditions to determine the effect of load on motor performance.

5. Data Analysis and Evaluation

The simulation results are analyzed in the form of:Speed vs. frequency graphs; Torque vs. time graphs; Slip comparison charts. These results are used to evaluate the efficiency of the V/f method in an open-loop system. The smaller the slip value and the more stable the torque and rotor speed, the better the system's performance is considered.

Based on the analysis, it is recommended to enhance the system toward closed-loop control or adaptive control for industrial applications that require high stability, precise speed control, and fast dynamic response.

3. RESULTS AND DISCUSSION

This test was conducted to evaluate the performance of an induction motor speed control system using the Volt per Hertz (V/f) technique in an open-loop configuration. The primary focus of the evaluation is to analyze the relationship between the input frequency, inverter output voltage, actual rotor speed, and the system's stability response to load variations.

In this process, the simulation was carried out based on the system configuration shown in Figure 1. The procedure began with the design of a sinusoidal pulse-width modulation (SPWM) circuit, which generates six control signals (S1–S6) as inputs to the three-phase inverter circuit. The inverter is controlled to convert a direct current (DC) voltage source into a three-phase alternating current (AC) voltage output for phases R, Y, and B, which is then supplied to the induction motor.

Subsequently, the motor was integrated with a monitoring system to observe various performance parameters, including rotor rotational speed, line-to-line voltage, stator current, slip, and electromagnetic torque. The simulation was performed by varying the input frequency to observe its effect on overall motor performance, particularly in responding to speed changes and maintaining stability in open-loop control mode.

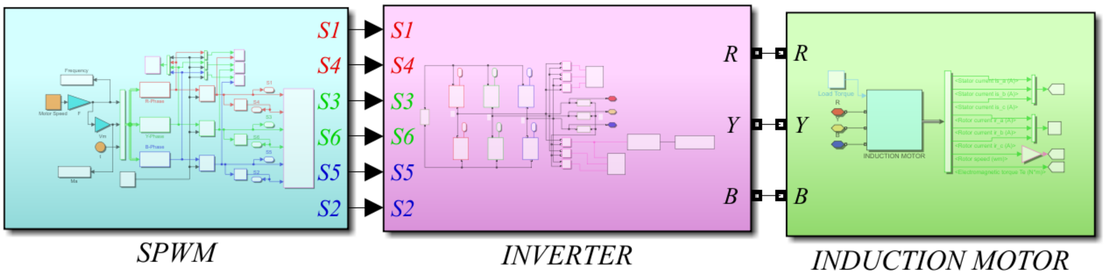

Fig. 1. Complete Testing Diagram

Figure 2 shows the block diagram of the simulation for generating signals to control a three-phase inverter in the induction motor speed control system. The main input comes from the specified frequency value (for example, 50 Hz), which is used to calculate the motor's synchronous speed (1500 rpm for a 4-pole motor) using equation (3). The frequency value is also used to determine the carrier wave period (Vm) and time (t).

Next, three sinusoidal reference signals for phases R, Y, and B (each shifted by 120°) are generated using the function f(u), representing the ideal output voltage of the inverter. These signals are compared with a triangular carrier signal using a comparator block to produce six SPWM signals (S1–S6). These SPWM signals serve as control signals for the inverter switches. S1, S3, and S5 are the original signals from the comparison process, while S4, S2, and S6 are obtained through a NOT (logical inversion) process. All six signals control the six switches of the three-phase inverter, thereby generating the three-phase AC voltage used to drive the induction motor. This diagram represents the entire inverter control signal generation process in an efficient and coordinated manner.

Figure 3 presents the three-phase inverter circuit based on SPWM signals, which is used to generate three-phase AC voltage from a DC source. The circuit consists of six IGBT switches (I1–I6) controlled by the S1–S6 control signals. Each IGBT pair (I1 & I4, I3 & I6, I5 & I2) is responsible for one output phase, namely R, Y, and B.

The SPWM signals are fed to the gate of each IGBT to control the switching on and off according to the required modulation pattern, forming a quasi-sinusoidal voltage for each phase. The output from each phase is supplied to the load (e.g., an induction motor) and equipped with RMS (Root Mean Square) voltage measurement to assess output voltage quality. In Figure 3, the RMS voltage value is recorded at approximately 278.7 Volts.

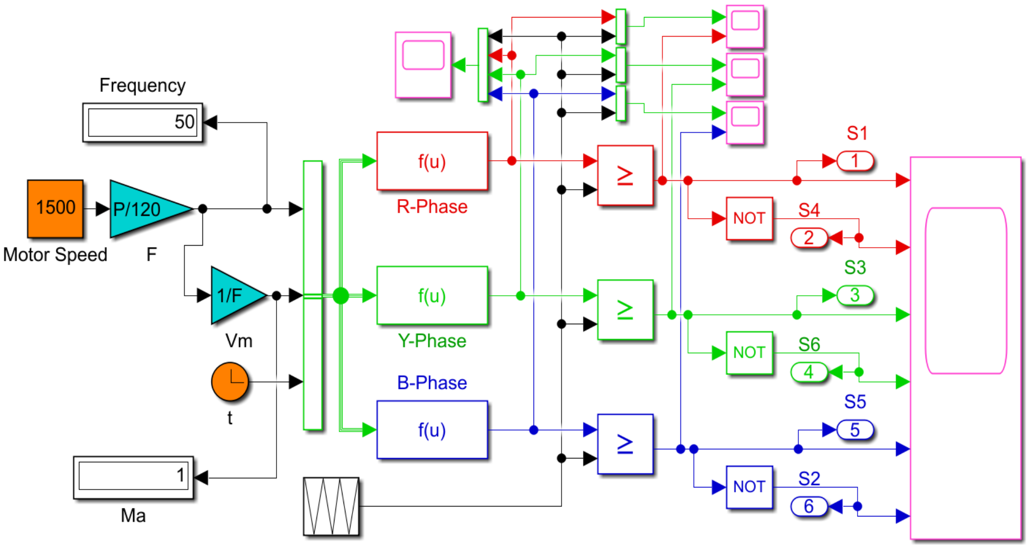

Fig. 2. Block Diagram of SPWM Signal Generation Simulation

In addition, the measurement and monitoring system is also presented with indicator blocks and real-time measurement. This circuit serves as an essential foundation for controlling three-phase AC motors with high efficiency and flexibility in speed and torque adjustment.

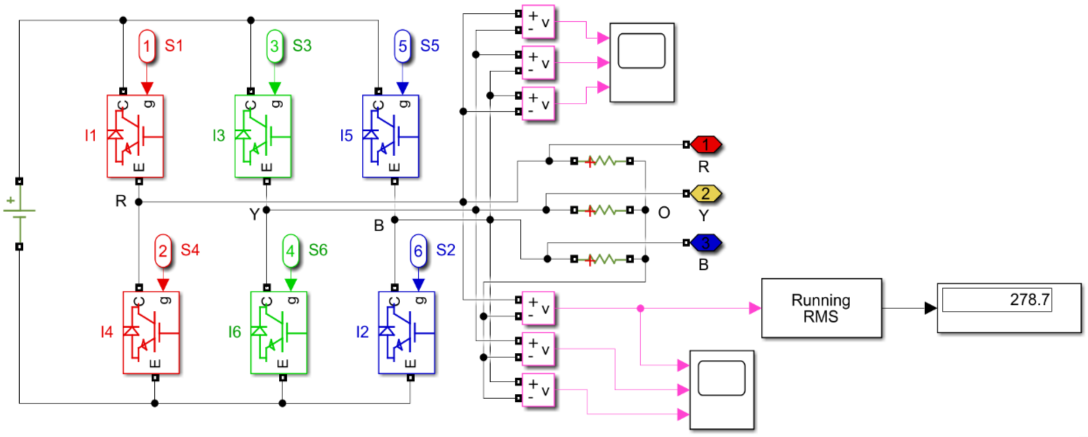

Fig. 3. Three-phase inverter circuit based on SPWM signal

Figure 4 presents the block representation of a three-phase induction motor simulation in the Simulink environment, where the motor is powered by a three-phase voltage supply (R, Y, B) and mechanically loaded through a “Load Torque (T)” element. The phase A, B, and C input voltages are applied to the motor stator terminals to create a rotating magnetic field that drives the rotor. Meanwhile, an external mechanical load (Tm) is applied to the rotor shaft to simulate real operating conditions experienced by the motor during operation.

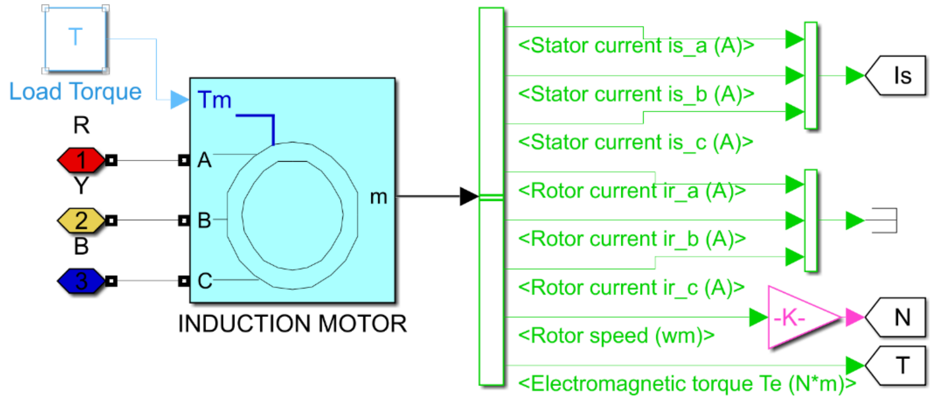

Fig. 4. Three-phase induction motor simulation block in the Simulink environment

The induction motor in this system produces outputs in the form of key electrical and mechanical parameters, which are then monitored to evaluate its dynamic performance. The observed parameters include stator currents in each phase (is_a, is_b, is_c), rotor currents (ir_a, ir_b, ir_c), rotor rotational speed (wm), and the generated electromagnetic torque (Te). All of these output data are connected to measurement and monitoring blocks, such as signal combiners, amplifiers, and indicators, to support comprehensive analysis.

This simulation model is highly useful for testing the performance of an induction motor under variations in load and supply voltage. Furthermore, this configuration also enables the design and testing of speed control strategies, such as the V/f method and vector control, by directly observing the relationship between load, current, speed, and torque in a dynamic and representative system.

4.1 No-Load Test Results

In the initial test, the induction motor was operated without any mechanical load. The input frequency was varied from 10 Hz to 50 Hz in increments of 5 Hz. The rotor speed was measured using a digital tachometer and then compared with the theoretical synchronous speed (n_s) calculated using Equation (3), with P = 4 (number of motor poles). The motor slip under no-load conditions was relatively small (<5%), resulting in the actual speed being close to the synchronous speed.

The results showed that the relationship between frequency and rotor speed is linear. This indicates that the implementation of V/f control successfully maintained flux stability and provided a consistent speed response. The constant V/f ratio applied was approximately 7.6 V/Hz.

Figure 5 presents the simulation results of a three-phase induction motor with three main parameters: stator current, torque, and speed. The stator current initially experiences a transient before reaching a stable three-phase sinusoidal waveform. The electromagnetic torque exhibits a significant overshoot of up to around 150 Nm, then decreases and stabilizes in the range of 50–60 Nm with slight fluctuations. The motor speed gradually increases until it approaches a steady-state value of around 1470 RPM, reflecting the characteristics of an induction motor operating in a 50 Hz system. The graph in Figure 5 demonstrates good dynamic response and operational stability of the motor under constant load conditions

Table 1. Summary of no-load system measurement data

Frequensi (Hz)	Output (V)	Speed Sinkron (rpm)	Actual Speed (rpm)	Slip (%)
10	76	300	287	4.3
20	152	600	580	3.3
30	228	900	872	3.1
40	304	1200	1164	3.0
50	380	1500	1470	3.3

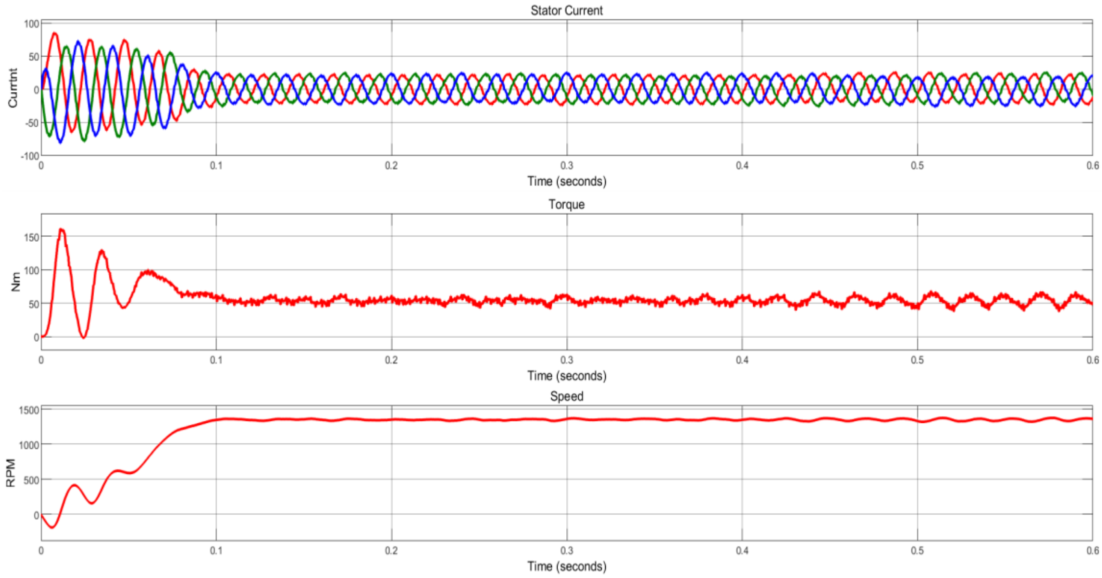

Fig. 5. Output diagram of the no-load system at 50 Hz frequency

Table 2. Simulation data of the induction motor under no-load conditions

Parameter	Range Value	Stable range	Time ti reach Stability	Unit
Stator Current	±100 A	±30–35 A	~0.2 s	Ampere (A)
Torque	0 – ~150 Nm	~50–60 Nm	~0.15 s	Newton-meter (Nm)
Speed	0 – ~1500 RPM	~1470 RPM	~0.3 s	RPM

4.2 Testing Results with Load

In the subsequent test, the motor was connected to a mechanical load in the form of a friction brake system to generate resistive torque. The motor speed was measured at fixed frequencies (20, 30, and 40 Hz) under both no-load and loaded conditions.

Table 3 Summary of measured data for the system with a 0 load

Frequency (Hz)	Speed No Load (rpm)	Speed With Load (rpm)	Del Speed (%)
10	580	556	4.1
20	870	830	4.6
30	872	832	4.6
40	1164	1110	4.6
50	1456	1388	4.6

Table 3 shows a decrease in speed when the load is applied; however, the reduction remains within a reasonable range (<5%). This indicates that the open-loop V/f system is capable of maintaining a relatively stable speed, even without an automatic compensation mechanism as found in closed-loop systems. The slip value increases as the load increases, which is a natural characteristic of induction motors.

4.2 System Performance Discussion

Based on the measurement results, it can be stated that the open-loop V/f control system successfully provides linear and stable speed regulation. This is in accordance with the basic principle of V/f, where the voltage-to-frequency ratio is kept constant to maintain flux and electromagnetic torque. In addition, the relationship between speed and frequency is close to full linearity, indicating that the inverter successfully produces a high-quality fundamental sinusoidal output. Table 5 shows that the system has a good dynamic response, with the speed reaching a steady-state of around 1300 RPM in a short time (~0.2 s). The small overshoot indicates that the speed control performance is fairly optimal.

Table 4 Summary of Speed and Torque Statistics

Parameter	Speed (RPM)	Torque (Nm)
Max	1369	136.9
Min	-185.3	-18.53
Peak to Peak	1554	155.4
Mean	1179	117.9
Median	1345	134.5
RMS	1238	123.8
Time Max	0.304 s	0.304 s
Time Min	0.0062 s	0.0062 s

Table 5 Speed Performance.

Parameter	Value (RPM)	Analysis
Max	1369	The motor is capable of reaching a high peak speed, indicating that the system’s maximum capacity is very good.
Min	-185.3	There is an initial oscillation or overshoot during startup; the negative value suggests a possible brief reverse rotation.
Mean	1179	The average speed is relatively high and demonstrates stability after the initial acceleration phase.
RMS	1238	It provides an overview of the system’s average kinetic energy, confirming its operational stability over a certain duration.
Stabilitas	—	The speed curve shows that the system reaches stability at around 0.2 seconds and maintains approximately 1300 RPM with minor ripple

Table 6 shows that the motor exhibits a fast and strong torque response during start-up, capable of sustaining high torque under load. Fluctuations in the initial phase are normal, and the torque stabilizes at around 100–120 Nm once the system reaches steady state.

However, under load conditions, there is a slight decrease in speed that cannot be compensated due to the absence of feedback. This is the main limitation of an open-loop system. If the application requires high precision or dynamic response to load changes, this system is not sufficiently reliable. Development toward a closed-loop system based on speed sensors and PI control or vector control becomes a logical solution for performance improvement.

In addition, the use of an SPWM-based inverter provides quite satisfactory results. The inverter output voltage waveform was observed to be close to sinusoidal, with the dominant harmonics kept under control. The modulation index was linearly adjusted to the input frequency, contributing to the stability of the output voltage at each speed level. From an efficiency perspective, this system is suitable for constant-load applications such as pumps, fans, and light conveyors. Its advantages lie in low cost, ease of implementation, and the absence of a need for complex additional sensors

Table 6. Electromagnetic Torque Performance

Parameter	Value (Nm)	Analysis
Max	136.9	A high peak torque at the start indicates the motor’s ability to overcome large inertia loads during start-up.
Min	-18.53	Indicates the presence of fluctuations or oscillations during the transient phase, although the values are not extreme.
Mean	117.9	The high average torque signifies that the motor operates efficiently in the medium to heavy load zone.
RMS	123.8	Demonstrates the system’s effective torque strength throughout the operating duration.
Stabilities	—	The torque curve experiences significant initial fluctuations, then tends to stabilize, although ripple remains present.

4. CONCLUSION.

The simulation results show that the open-loop V/f-based induction motor speed control system is capable of maintaining a linear relationship between frequency and rotor speed with a small slip (<5%). The system can reach steady-state speed quickly (~0.2 s), produce a sufficiently large electromagnetic torque, and maintain stability during load changes. The average speed value reaches 1179 rpm, and the average torque is 117.9 Nm, with efficient performance under constant-load conditions.

The open-loop V/f method is very suitable for light industrial applications such as fans, blowers, and pumps, which do not require high-precision speed control. This system is economical, simple to implement, and reliable as long as the load is constant or varies only slightly.

To meet the needs of industrial applications that demand high speed stability and adaptive response to load changes, it is recommended to develop the induction motor speed control system from open-loop mode to a closed-loop or adaptive control system. The implementation of a speed sensor and the use of controllers such as PI or vector control will improve speed regulation precision, reduce slip, and enhance the motor’s response to dynamic loads, thereby supporting the efficiency and reliability of the system under varying operating conditions.

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