Grenze International Journal of Engineering and Technology, January Issue

Sinusoidal Pulse Width Modulation for Speed Regulation of a Three-Phase Induction Motor under Load

Basavarajappa S R[1], Manjunatha H M[2], Anjaneya L H[3], Karibasavaraju T S[4] and Arunkumar P[5]
[1-5]Department of Electrical and Electronics Engineering, Bapuji Institute of Engineering and Technology, Davanagere, Karnataka, India
Email: basavarajsr@bietdvg.edu, manjunath.hm1986@bietdvg.edu, anjudvg@yahoo.com, kbrpower440@gmail.com, arunkumarp584@gmail.com

***Abstract*— Adjustable industrial speed drives require closed-loop speed control. Three-phase voltage source inverters (VSI) need adjustable voltage and frequency. Sinusoidal pulse width modulation (SPWM) is used to regulate the speed of an induction motor (IM) powered by a three-phase VSI. PI controllers reduce steady-state speed inaccuracies. In MATLAB-Simulink, the performance of the closed-loop speed control system is evaluated. The motor's speed decreases as the load torque increases, but it quickly recovers with minimal undershoot during a short settling time. Simulations demonstrate that the speed controller has enhanced dynamic response, allowing it to adjust the induction motor's speed and torque. The simple, cost-effective Volts/Hertz (v/f) control method for a three-phase induction motor is widely used; however, its dynamic performance is limited. A closed-loop system with an appropriate controller effectively regulates speed. An accurate mathematical model of the system is essential for the Proportional-Integral (PI) controller, which is commonly employed. Therefore, a robust controller may impact the simplicity of the v/f control system.**

***Index Terms*— Closed Loop Control, SPW Modulation, PI Controller, Induction Motor, Dynamic Load.**

I. INTRODUCTION

Three-phase induction motors are electrical machines that act as the workhorses of industry. They are the most commonly used type due to their durability, low maintenance, high reliability, and the absence of sparks, as they do not have commutators and brushes. These motors are especially popular because they can start and operate independently of each other. Typically, induction motors operate at a steady or desired speed, even when the load torque changes. The primary methods for controlling their speed are vector control and scalar control, also known as v/f control.

Closed-loop speed control ensures that, regardless of load conditions within the motor's rated capacity, the speed stays at the desired or set point. This method is commonly used to regulate motor speed in response to changing load conditions. It relies on feedback to enhance the motor's performance, safety, and efficiency. According to [1], PWM systems represent a new development in terms of widespread industrial applications.

Grenze ID: 01.GIJET.12.1.22

They enabled variable-speed IM drives in the marketplace due to the availability of high-speed switching devices such as IGBTs. The ability of PWM switching converters to generate complex wave shapes of any frequency and phase has opened up the possibility of performing IM drives. In electrical drives, various sensors and control algorithms manage the motor's speed with appropriate control methods.

In [2], IM is a singly fed machine; it draws its excitation current from the source to set up the rotating field in the air gap, which is essential for its operation. The interaction between the RMF and rotor current produces torque. Speed control methods, such as slip control and frequency control, were discussed. The speed depends on the power frequency and the number of poles in both the stator and rotor. They are widely used in various sectors, including industrial automation, power generation, transportation, and agriculture. In industrial automation, they drive conveyor belts, pumps, and fans; in power generation, they are utilised in wind turbines and hydroelectric plants; in transportation, they are employed in electric vehicles and rail systems; and in agriculture, they are used in irrigation systems and farm equipment.

In [3], MATLAB simulations were conducted to determine the best method for controlling the speed of a 3-phase IM using a 3-phase inverter. This research employed two different approaches. The first involved generating a conventional pulse with a pulse generator, while the second utilised SPWM, which was further divided into open-loop control and closed-loop control. The goal was to control the speed of the three-phase IM with a three-phase inverter. A review of these PWM methods and related simulations was performed to achieve this. The closed-loop control method addressed the limitations of the open-loop approach by allowing parameter adjustments without stopping operation. In the work [4], speed control of the IM is achieved using MATLAB/Simulink by adjusting the pulse width using the variable-voltage method. In contrast, the variable voltage and variable frequency (VVVF) method maintains the v/f ratio constant throughout the entire speed range, thereby improving machine performance and efficiency. Study [5] investigated the speed regulation of an induction motor powered by a three-phase VSI using PWM techniques and a universal bridge. A PID controller was designed to regulate the peak DC link voltage of the inverter. MATLAB/Simulink was used to evaluate the performance of both open-loop and closed-loop speed control systems. The simulation results demonstrated that the speed controller provided a robust dynamic response, effectively managing the induction motor and resulting in enhanced performance. The study in [6] explores the speed control of 3-phase induction motors and tracks the speed using Simulink. Several methods are available for this, including stator voltage control and rotor resistance control. The v/f control method is the most preferred and commonly used technique for regulating the speed of IM, resulting in optimal performance and high efficiency. During power shortages, conserving excess energy is crucial. The v/f control of 3-phase induction motors is favoured due to its simplicity and cost-effectiveness, despite its inferior dynamic performance. A closed-loop system with an appropriate controller is employed to achieve efficient speed regulation. The commonly used PI controller requires an accurate mathematical model of the system to be effective. The study [7] discusses the speed regulation of induction motors in industrial applications by adjusting the duty ratio of switches. In this context, voltage and frequency are adjusted to control motor speed. This document presents the performance and evaluation of a VSI feeding an induction motor drive. PWM technology is employed to modulate voltage and frequency. In the research work [8], the frequency of the stator voltage is controlled to compensate for errors using frequency compensation control (FCC). The three-phase induction motor is operated in a constant torque mode. Implementing a closed-loop system with a PI controller has demonstrated a significantly improved method for regulating the speed of an IM while maintaining a constant maximum torque. In the work [9], a dynamic model of IM was developed using its equivalent circuit in MATLAB. This model has provided adequate responses in terms of speed and torque control. The simulation study [10] explores the space vector PWM technique to control the speed of the IM based on its d-q equivalent circuit.

The following objectives are designed to address the problem statement:

- Operate an induction motor in a closed-loop system with a three-phase inverter under changing load conditions.
- Implement a speed controller using a PI controller that adjusts the motor torque to reach the desired speed response.

II. Materials and Methods

A. Development of the Simulink Model

Closed-loop speed control of a three-phase IM uses a feedback system to continuously monitor the motor's speed and adjust the control inputs to achieve the desired speed, as shown in Fig. 1 and Fig. 2. This model focuses on implementing a three-phase variable-speed induction motor drive using a VSI in MATLAB/Simulink.

B. Algorithm

Procedure to draw the Simulink model with entries and simulation:

- Open the MATLAB-Simulink window and select a blank or new model file.
- Go to the library browser, select components from the Simulink library, or type the name of the element in the model file.
- Place the components and connect them according to the circuit diagram.
- Save the model file with the correct name and extension .mdl.
- Enter the values for the respective components as shown in Table I.
- Simulate the model with a simulation time of 2 seconds.
- Observe the characteristics in the Scope and variable files in the workspace window.

TABLE I. COMPONENTS DATA

Component/Block	Select/enter the values by double-clicking on the component
Asynchronous Machine	Configuration: Rotor type: Squirrel-cage Squirrel-cage preset model:15: 5.4HP (4kW), 400V, 50 Hz, 1430rpm Mechanical input: Torque Tm Reference frame: Rotor
DC Voltage Source	Parameters: Amplitude(V): 400/sqrt (3) *sqrt (2) *2
Three-Phase Voltage Source Inverter	Parameters: Configuration: Yg Phase-to-phase voltage (Vrms): 400 Phase angle of phase-A (degree): 0 Frequency (Hz): 50 (Disable/uncheck Impedance: Internal)
Step	Step time: 0.5, Initial value: 0, Final value:1, Sample time: 0
Bus Selector	Remove default signals. Select signals in the bus: Stator measurements: Stator current Ia (A) Mechanical: Electromagnetic torque (N-m) Rotor speed ωm (rad per sec)
RMS	Fundamental frequency (Hz): 50
PID Controller	Controller: PI Time domain: Continuous time Controller parameters: Source: Internal Proportional (P): 0.5 Integral(I): 8 Select tuning method: Transfer function-based initial conditions Source: internal, Integrator: 0 External reset: none
Scope	Right click: Signals and ports: Number of input ports: 3
Gain	Gain4: 60/(2*pi), Gain1: 100, Gain3: 100, Gain2: 1/735.5
To Workspace	Variable name: Name of the respective output variable (Example: Te) Save format: Array

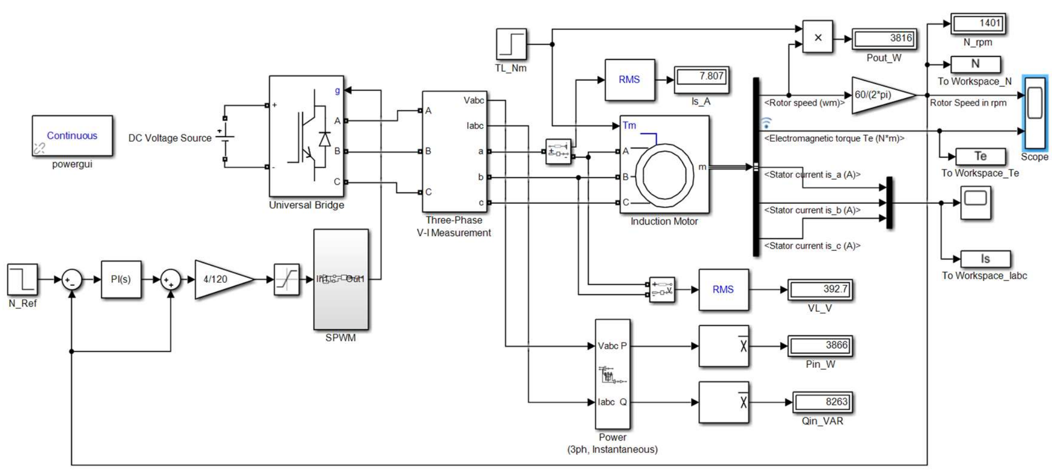

Figure 1. Simulink model of speed control of a three-phase induction motor

The direct current voltage source is converted to an alternating current source using a VSI. The DC source originates from a renewable energy source, specifically a solar panel, and is integrated with a battery. The VSI is then connected to a three-phase voltage and current measurement system that displays both voltage and current. This setup is linked to the stator of a squirrel-cage three-phase induction motor. The motor outputs, such as speed, electromagnetic torque, and stator currents, are selected from a bus selector. The rotor speed, measured in rad/sec, is converted to rpm. This rotor speed acts as a feedback signal connected to the switch. The error detector calculates the steady-state speed error relative to the reference speed. This error is processed through a PI controller to reduce the steady-state error. The resulting signal is added to the actual speed and converted into frequency. It is then fed into a frequency limiter and converted into rad/sec. This signal is integrated and divided by the rated speed, producing two control signals (u1 and u2) for the sinusoidal pulse width modulator (PWM). The PWM generates gate pulses for the IGBTs in the three-phase VSI, ensuring that the voltage-to-frequency ratio remains constant.

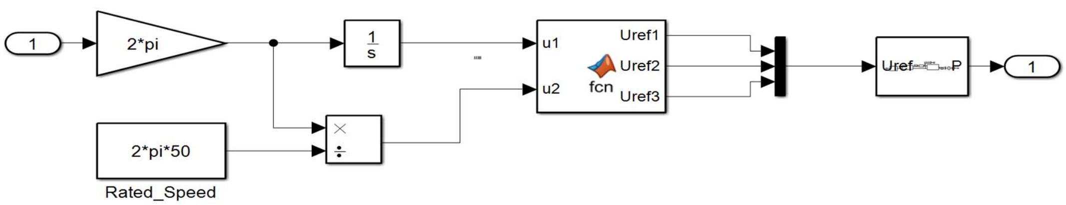

Figure 2. Simulink of the SPWM generator

The speed control of AC motors is more complex than that of DC motors. Various methods, including indirect vector control and scalar control, are employed to regulate motor speed. Scalar control is a simple, open-loop control type; however, it responds slowly to transients and is unsuitable for motors with dynamic behaviour. Open-loop speed control methods lack stability during continuous and intermittent duty cycles of motors. Closed-loop control, which uses speed as a feedback signal, is essential for dynamic AC drives in industrial applications.

III. Results and Discussion

A. Case-1: Reference Speed = 1400 rpm (step change from 1430 to 1400 rpm) at a constant load torque of 26 Nm. Fig. 3 shows the time versus rotor speed and electromagnetic torque characteristics of the induction motor. Initially, the rotor speed is 1430 rpm. At time t = 1 second, there is a step change from 1430 to 1400 rpm at a constant torque T = 26 Nm.

Fig. 4 compares the rotor speed and torque over time. At t = 0.6 seconds, the reference speed is reduced to 1400 rpm and then further reduced to 1350 rpm. It is subsequently increased to 1380 rpm and finally to 1450 rpm, all at a constant load torque. It is the constant torque mode of operation, which controls the speed of the motor below its rated speed. Under these conditions, a further increase in speed causes the rotor speed to remain constant at 1436 rpm, as tabulated in Table II. The settling time of speed is less than 0.2 seconds. The stator current waveform shown in Fig. 5 indicates that the motor current remains constant.

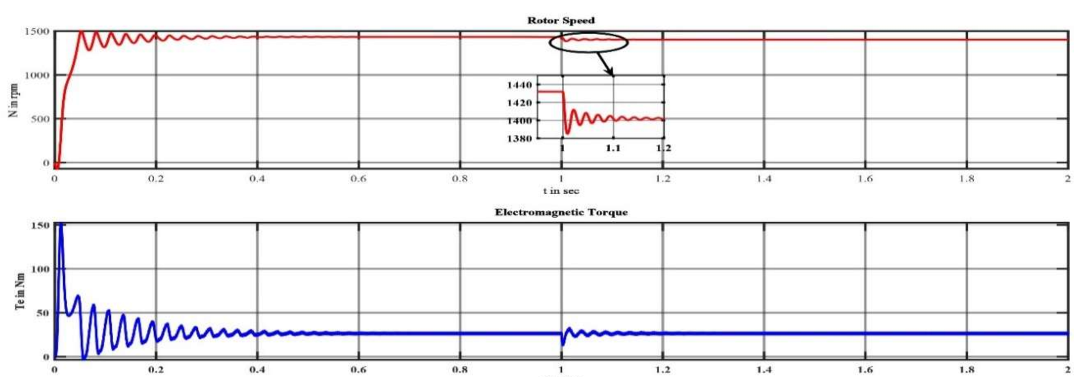

Figure 3. Rotor speed and electromagnetic torque to time responses for a step change in speed of 1400 rpm

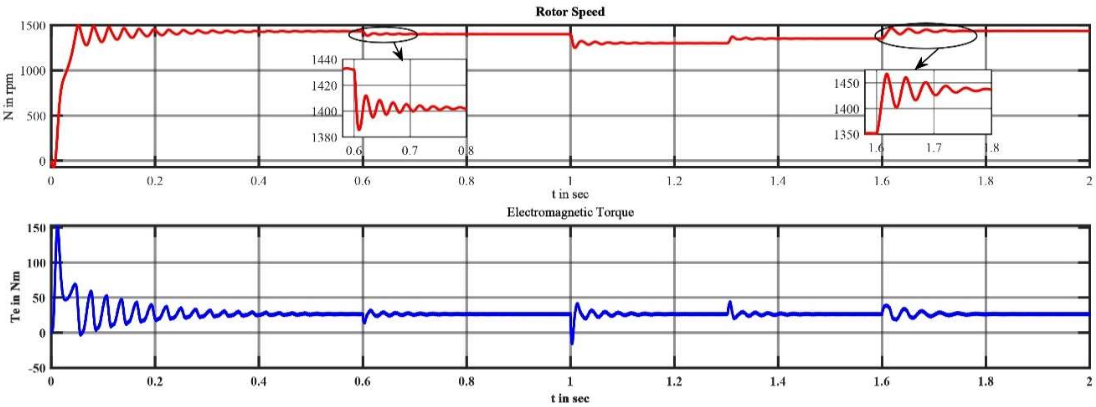

Figure 4. Rotor speed at constant electromagnetic torque to time responses

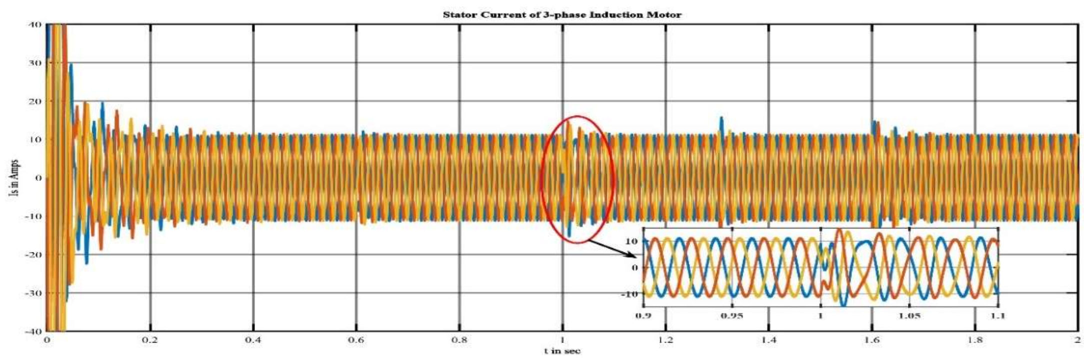

Figure 5. Stator current waveform at constant torque of 26 Nm

B. Case-2: Torque = 20 Nm (step change in torque from 0 to 20 Nm) at a reference speed of 1430 rpm. At the initial stage, the rotor's reference speed is 1430 rpm. At t = 1 second, a step change in load torque from 0 to 20 Nm occurs; the motor continues to run at the same reference speed of 1430 rpm, as shown in Fig. 6. In this case, the settling time is less than 0.2 seconds. In Fig. 7, at t = 0.6 seconds, the load torque increases from 5 to 10 Nm, then further increases to 20 Nm, and subsequently decreases to 15 Nm, causing the rotor speed to decrease/increase; however, it stabilises and runs at a constant or reference speed of 1430 rpm. When the torque increases beyond the pullout torque (28 Nm), the speed decreases. It is tabulated in Table III. Fig. 8 presents the variations in stator current, which are directly proportional to the corresponding changes in torque. In the closed-loop operation, the PI controller quickly reduces the steady-state error in speed and torque deviations.

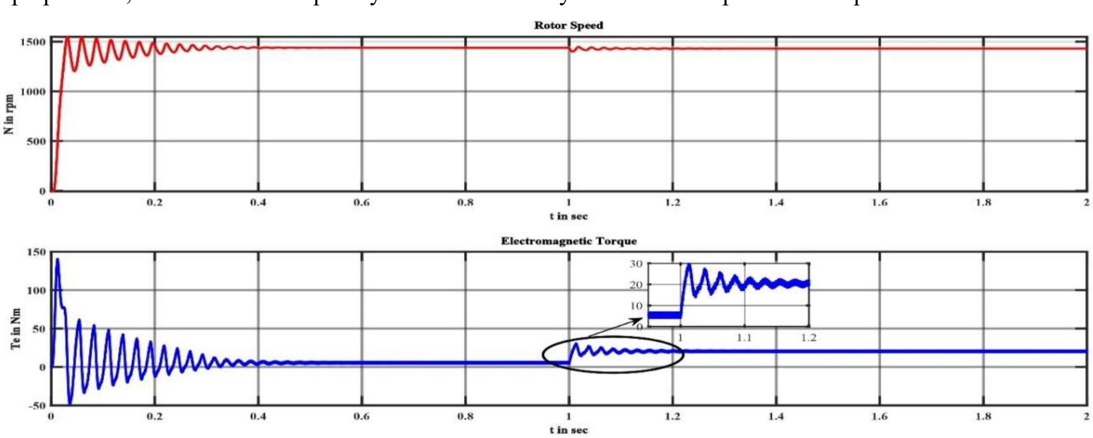

Figure 6. Rotor speed and electromagnetic torque to time responses for a step change in torque of 20 Nm

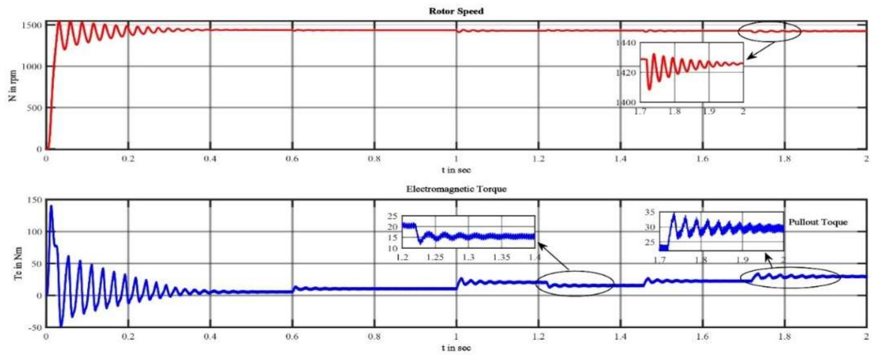

Figure 7. Electromagnetic torque at constant rotor speed to time responses

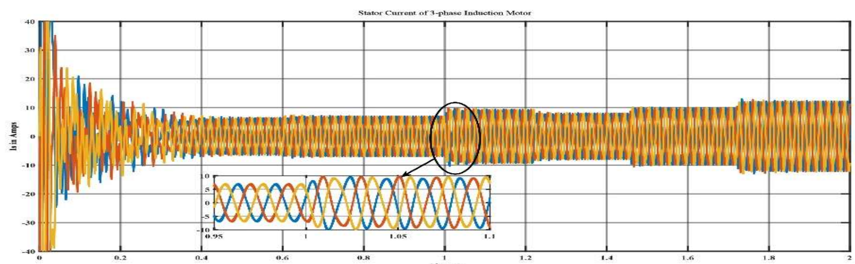

Figure 8. Stator current waveforms at variable torque of 5 to 30 Nm

Table II shows how rotor speed is regulated at a constant load torque by adjusting the reference speed in closed-loop operation. As the reference speed increases, both the rotor speed and output power increase until the speed reaches the rated value of 1430 rpm. Beyond this, rotor speed and output power stay constant. Table III illustrates rotor speed regulation at a fixed reference speed by changing the load torque. As the load torque increases, the output power also increases, but the rotor speed remains steady until it reaches the pull-out torque of 28 Nm. After exceeding this torque, the speed decreases. Fig. 9 and Fig. 10 illustrate the variations in speed, power, and torque.

TABLE II. SPEED AND POWER AT CONSTANT TORQUE

Sl. No.	Load Torque (Nm)	Reference Speed (rpm)	Stator Current (A)	Stator Voltage (V)	Output Power (W)	Rotor Speed (rpm)
1	26	1300	8.030	352.7	3539	1300
2		1360	7.937	375.3	3703	1360
3		1380	7.789	379.0	3757	1380
4		1400	7.695	400.0	3812	1400
5		1420	7.818	395.1	3866	1420
6		1430	7.767	399.1	3893	1430
7		1450	7.781	400.0	3911	1436
8		1470	7.780	400.0	3911	1436
9		1500	7.780	400.0	3911	1436

TABLE III: SPEED AND POWER AT CONSTANT REFERENCE SPEED

Sl. No.	Reference Speed (rpm)	Load Torque (Nm)	Stator Current (A)	Stator Voltage (V)	Output Power (W)	Rotor Speed (rpm)
1	1430	5	4.216	391.2	749	1430
2		10	4.788	388.4	1497	1430
3		15	5.623	386.2	2246	1430
4		20	6.491	392.3	2995	1430
5		23	7.089	396.6	3444	1430
6		26	7.767	399.1	3893	1430
7		28	8.24	399.8	4193	1430
8		29	8.475	400.0	4338	1428
9		30	8.713	400.0	4479	1426

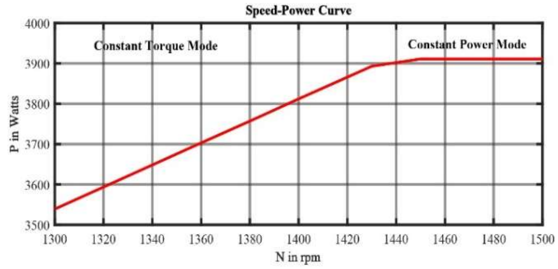

Figure 9. Speed Versus Power Curve

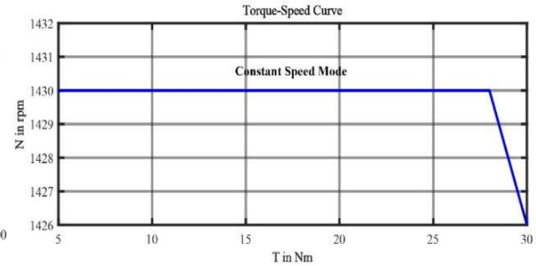

Figure 10. Torque Versus Speed Curve

IV. CONCLUSIONS

The Simulink model for closed-loop speed control of a three-phase induction motor has been created. A sinusoidal pulse-width modulation (SPWM) technique is used to regulate speed within a closed-loop system. This method offers more efficient and reliable operation for both continuous and intermittent duty cycles, ensuring smooth speed control across various industrial applications. A simple v/f control method for the three-phase induction motor is proposed. The simplicity of this closed-loop control system depends on the approximately linear relationship between load torque and slip speed when the stator flux remains constant. When the load torque increases slightly, the motor speed decreases, resulting in the generation of direct and quadrature axis currents. The transient responses of current, torque, and speed are analysed in cases 1 and 2, and the approach for speed control and tracking of the induction motor is outlined. The results indicate that a closed-loop SPWM system is the most efficient method for regulating the speed of a three-phase induction motor using a three-phase inverter.

ACKNOWLEDGMENT

The authors are grateful to the head of the Bapuji Institute of Engineering and Technology, Davanagere, Karnataka, for their support, encouragement, and facilities in conducting this research.

REFERENCES

[1] Theodore Wildi, “Electronic Controls of Alternating Current Motors” in Electrical Machines, Drives, and Power Systems, Pearson, 5th Edition, ch. 23, pp. 575-629, 2002.

[2] I.J. Nagrath and D.P. Kothari, “Induction Machines” in Electric Machines, 4th Edition, McGraw-Hill, ch. 9, pp. 593-688, 2010.

[3] Mohit Desai, Deepak Mishra, Rohan Patel, and Ketan Bhavsar, “MATLAB Simulation of Closed-Loop Speed Control of Three-Phase Induction Motor Using Slip Control Method and Sinusoidal PWM Technique”, International Journal of Engineering Research and Technology, vol. 10, no. 9, pp. 509-514, 2021, https://doi.org/10.17577/IJERTV10IS090170.

[4] Rajkumar Yadav, Manoj Kumar Kar, and Arun Kumar Singh, “Speed Control of a Three-Phase IM with Closed-Loop Control Scheme”, in book: Recent Advances in Power Electronics and Drives, pp. 43-55, 2022, https://doi.org/10.1007/978-981-16-9239-0-4.

[5] H. Hartono, R. I. Sudjoko, and P. Iswahyudi, “Speed Control of Three-Phase Induction Motor using Universal Bridge and PID Controller”, Journal of Physics: Conference Series Indonesia, vol. 1381, pp. 1-8, 2019, https://doi.org/10.1088/1742-6596/1381/1/012053.

[6] G. N. Madhu, Patela Naik L., “Speed Control of Induction Motors Using Proposed Closed-Loop V/F Control Scheme”, International Research Journal of Engineering and Technology, vol. 06, no.8, pp. 1429-1432, 2019.

[7] Bhagat B., Singh G., “Performance and Evaluation of Voltage Source Inverter-Fed Induction Motor Drives”, International Research Journal of Engineering and Technology, vol. 6, no. 2, pp. 1168-1171, 2019.

[8] Koga K., Ueda R., and Sonoda T., “Constitution of V/F Control for Reducing the Steady-State Speed Error to Zero in Induction Motor Drive System”, IEEE Transactions on Industry Applications, vol. 28, no. 2, pp. 463–471, 1992, https://doi.org/10.1109/28.126757.

[9] P. Rajesha, and M. Sharanya, “Dynamic Simulation for Three-phase Induction Motor and Speed Control Using Matlab/Simulink”, Turkish Journal of Computer and Mathematics Education, vol. 12, no. 2, pp. 825- 834, 2021.

[10] Heba Abdul-Jaleel Al-Asady, Hassan Falah Fakhruldeen, “Volts/Hz Control of Three Phase Induction Machine: Matlab/Simulink”, Iraqi Academics Syndicate International Conference for Pure and Applied Sciences, Journal of Physics: Conference Series, vol. 1818, no. 1, pp. 1-12, 2021, https://doi.org/10.1088/1742-6596/1818/1/012089.