

# Study of performance the 3-phase induction motor that drives by using scalar and vector control with variable speed loading

Omran Alabedalkhamis, Baran Karahan, İbrahim İdiz, Hüseyin Alptekin, Enver Ediz Erol

EFG Electrical Company, AR-GE Center, Diyarbakır, Türkiye

## Article Info

### Article history:

Received Sep 30, 2025

Revised Jan 16, 2026

Accepted Feb 26, 2026

### Keywords:

Induction motor

Scalar control

Sinusoidal pulse width

Space vector modulation

Variable-speed drive systems

Vector control

## ABSTRACT

Induction motor performance and efficiency greatly depend on the applied control technique, particularly in variable- and fixed-speed industrial applications. This paper aims to comparatively assess scalar control and vector control strategies for three-phase squirrel-cage induction motors. Using a simulation-based approach in MATLAB/Simulink, scalar control with sinusoidal pulse width modulation (SPWM) and vector control with space vector modulation (SVM) are built and analyzed under constant, variable, and bidirectional speed loading situations characteristic of a drive system. The results demonstrate that vector control provides greater speed regulation (about 93% compared to scalar control), reduced torque ripple (about 97% compared to scalar control), lower current stress (about 94% compared to scalar control), and improved dynamic responsiveness compared to scalar control, especially during transient operation. The paper is limited to numerical simulations. This paper's biggest contribution is a clear, practical comparison which provides performance- and cost-oriented guidelines for selecting appropriate induction motor control strategies in several applications.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



## Corresponding Author:

Omran Alabedalkhamis

EFG Electrical Company, AR-GE Center

Diyarbakır, Türkiye

Email: omran.khamis@gmail.com

## 1. INTRODUCTION

Asynchronous motors, particularly squirrel cage, are thought to be the most prevalent electrical devices in industrial applications in recent years, whether they are used as generators in wind energy or motors in pumps, electrical vehicles, fans, elevators [1]-[8], due to their many benefits over other kinds of electrical devices, such as simple structure, low fabrication, less maintenance, ruggedness, low cost, high efficiency, reliability [9]-[12], in addition to faster response to load disconnection [13]. Furthermore, IM production can operate at higher temperatures and speeds than others because it does not require the usage of rare magnetic materials [14], [15].

An effective controller is always required to manage the motor parameters and regulate flux and torque in order to enhance the performance of an asynchronous motor drive [16]. Since the rotor and stator currents can easily control the magnetic flux and torque independently, DC machines were crucial in the early days of variable speed drive applications. In addition to low efficiency of the IM speed control techniques, the usage of asynchronous motor has been limited to the applications that have constant speeds [17]-[19].

The scalar control, also called V/Hz, and vector control, also called field-oriented control, are the two main control techniques used to regulate asynchronous motor speed. The first strategy is simple to use,

inexpensive, and produces good steady state outcomes. Nevertheless, this strategy provides a delayed transient reaction, making it ineffective when dealing with dynamic systems [20]. Conversely, FOC has a quick and superior transient response despite being more complicated [21]-[23].

Scalar control involves controlling the magnitude of frequency or voltage of supply fed to machine. The V/f control strategy is based on the idea to preserve a constant flux of air gap by adjusting stator frequency and voltage in order to maintain a constant V/f ratio [24]. The open loop V/f technique has inadequate speed regulation. However, flux increases and the gap between the desired and actual speeds decreases as the V/f ratio rises. Therefore, speed regulation can be enhanced by altering the V/f ratio [25]. The square of the terminal voltage determines the IM's output torque. In the voltage control approach, an increase in voltage is used to enhance torque. A redesigned PI controller with V/F scalar control enhance both speed and torque performance. However, the issue is that terminal voltage has a limit that, if exceeded, will have a detrimental impact on insulation [26].

Scalar control is only used in applications like pumps where the system's dynamic behavior performance requirements are less demanding [27]. Because the speed of rotor will be somewhat slower than the synchronous speed and frequency is only control variable in this technique, the motor's speed is unable to accurately controlled [28]. voltage source inverters have been typically used to control speed by adjusting frequency and voltage [29]-[31].

Field oriented control (FOC), also known as vector control, is an effective way to regulate asynchronous motor's torque, speed, or both. Like to DC machines, FOC divides the complicated stator currents into two orthogonal components, one of which controls speed and the other electromagnetic torque. FOC has more stability, quick torque response, and precise speed control [32]. Accurate rotor flux placement must be obtained in order to carry out the frame transformation [33], [34]. The best performance over the inverter losses is offered by a hysteresis-band pulse-width modulation (PWM) [35].

Various control techniques have been introduced in the past in which the direct torque control (DTC) have proved to be most commonly used technique. With promising features like quicker torque response and enhanced dynamic performance, DTC has become a potent instrument as shown in Figure 1. Although the term DTC often is associated with hysteresis methods, we can classify also indirect self control (ISC) as a DTC method. This route is followed also in the survey on DTC schemes given in [36]. Torque ripples and slow startup when load changes are common drawbacks of traditional DTC [37]. Recent advancements in DTC systems include the use of unified flux control scheme [38], stator flux vector control in field weakening region [39], [40], fuzzy logic [41], FPGA [42], [43].

An effective controller for the DTC induction motor drive must be created for crucial applications. The difficulty of an effective PI controller for high performance increases significantly since the IM is a heavily cross-coupled machine. Conventionally the PI controllers are tuned by Ziegler Nichols tuning method. However, it is observed that the controller performance deteriorates under varied drive operating conditions. Studies of the literature have revealed that the application of stochastic optimization techniques to achieve the optimal values of PI controllers is becoming more and more important [44]-[49].

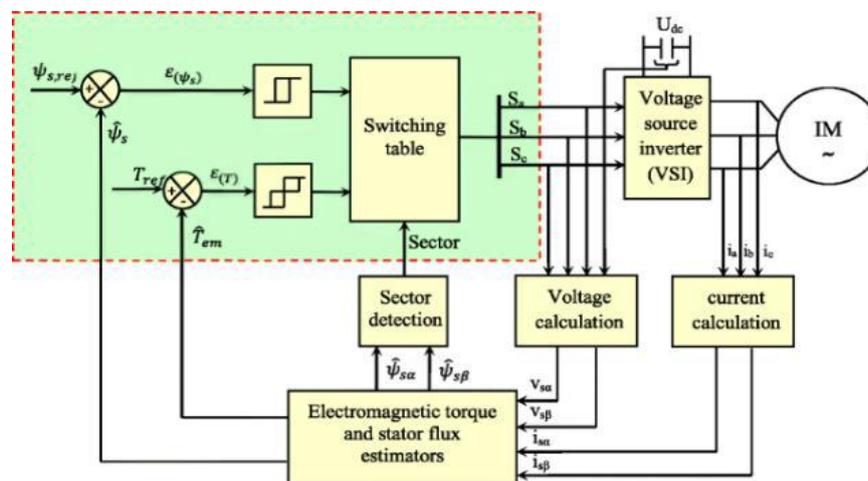


Figure 1. Schematic diagram of DTC using VSI fed IM

The modified DTC controller used in the proposed study replaces the hysteresis controllers for torque and flux with PI controllers. The drawback of conventional DTC is that the errors in torque, flux are within the designated band limits, which restricts the range of switching selection for inverter [50], [51]. In the modified DTC the difference between the reference and actual speed is processed by the speed PI controller to generate a torque command as shown in Figure 2 [52], [53].

Abebe *et al.* [54], researchers have used space vector pulse width modulation (SVPWM) method to control the inverter fed IM under DTC strategy as shown in Figure 3. Shankar [55], by separating the motor's flux and torque components, scalar control and vector control increase performance, including quicker reaction times, more accurate speed and torque, and less harmonic distortion. But this study has not applied under various load and speed conditions. DTC has higher dynamic response than FOC, however it has issues like excessive torque ripple [56]-[58]. There are several ways to regulate an asynchronous motor's speed, such as control of rotor resistance [59].

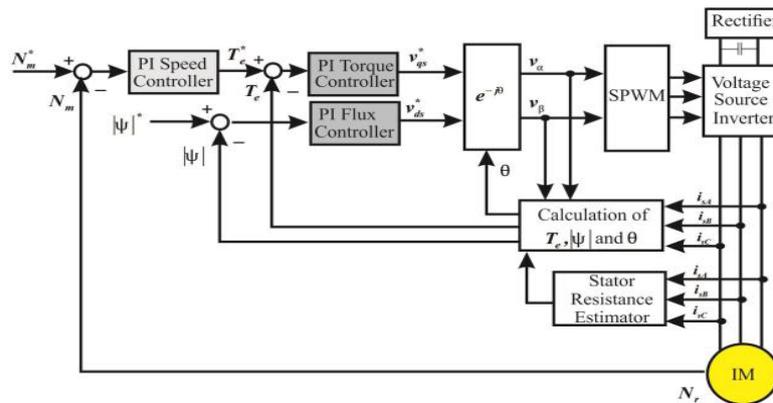


Figure 2. Schematic diagram of DTC using PI controllers

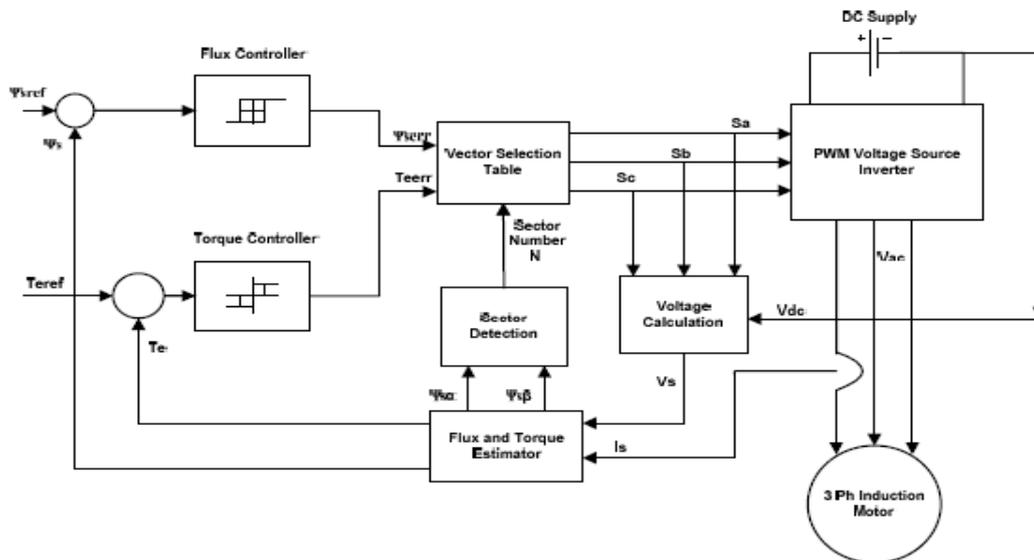


Figure 3. Schematic diagram of DTC using PWM

Indirect vector control for asynchronous machine has presented in [60], which provide high dynamic responses for any speed as shown in Figure 4. modelling and simulation of indirect vector control for asynchronous machine drive using two and five level inverters has been presented in [61]-[63]. Hasan *et al.* [64], performance of speed for asynchronous machine using a vector control has been presented. The main focus is to monitor the dynamic speed performance of asynchronous machine. The outcome demonstrates that presented technique has a negligible electromagnetic torque ripple. Khoury *et al.* [65], current controller and speed controller have been designed using PID and field weakening techniques, consequently, the system

produced good transient and steady state responses and reached the intended speed. Many approaches have been created and researched in relation to the low-speed operation of sensor-less vector control [66], [67]. Fukumoto *et al.* [68], Several observers are added to the sensor-less vector control to improve performance. As a result, circuit complexity rises as shown [69]. The performing of indirect vector-controlled asynchronous machine has been proposed with many level inverters at [70]. Space vector-based multi-level inverter (MLI) supplied vector-controlled asynchronous machine analysis for operation of low-speed, as illustrated in Figure 5, has been presented in. Motor performance is negatively impacted by variations in load speed. This circumstance is one of the problems that has been studied from the past to the present; recommendations and solutions have been developed [71].

Jain *et al.* [72], it is observed that it improves the performance of conventional control techniques when combined with proportional-integral-derivative (P-PIPID) controller [73]. Many studies have proposed controls like flux to improve the performance of speed control [74]. There are techniques such as Kalman Filter, placement, adaptive, finite elements, observer based, matrix theory, sensor-less [75]-[84].

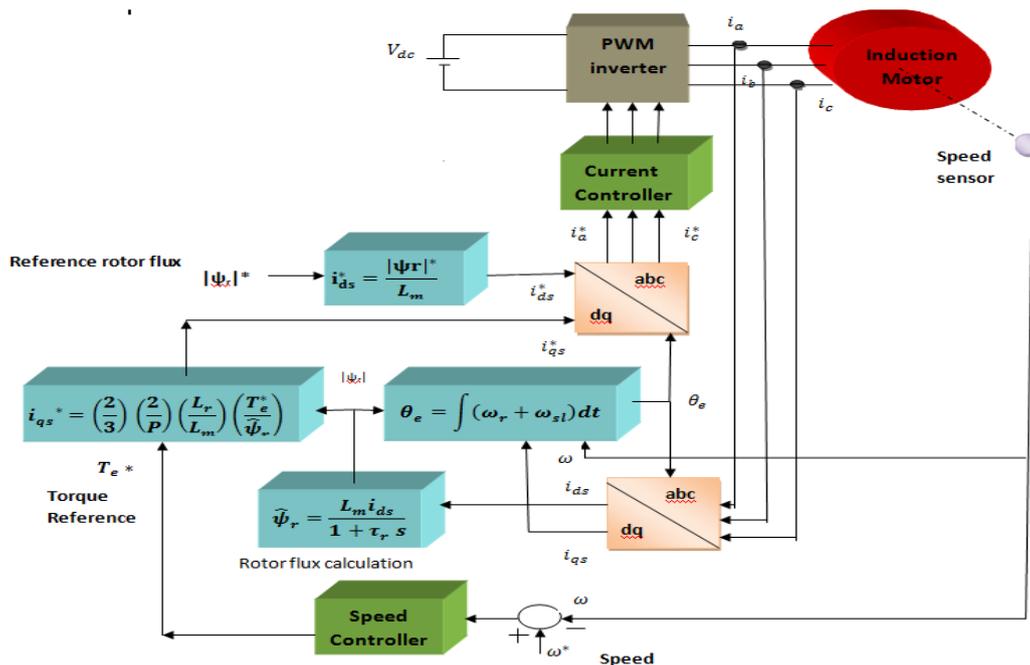


Figure 4. Schematic diagram of indirect vector control

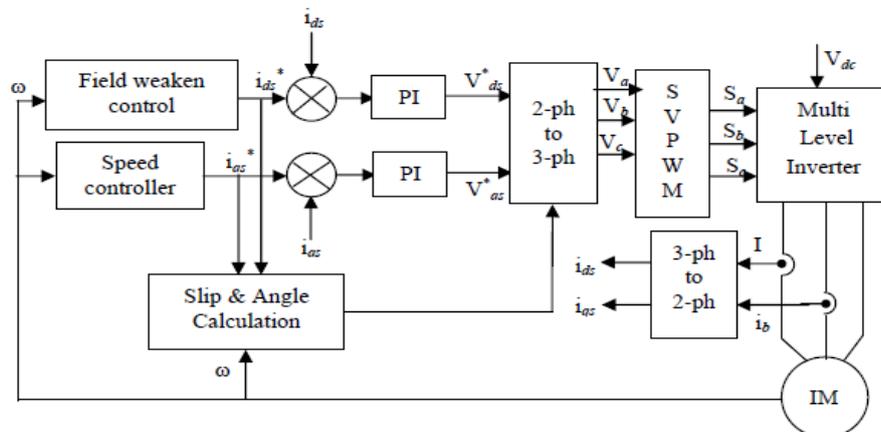


Figure 5. The concept for multi-level inverter's schematic diagram

In speed control, some numerical analytic techniques are directly applied such as techniques of interpolation [85]-[88]. The performance of the PI speed controller, which was developed for indirect vector

control, is examined for the control system’s optimal response in [89]. The fuzzy logic controller’s settling time and dynamic response to abrupt load fluctuations are compared with the PI controller’s has been presented in [90]. Holmes *et al.* [91] a comparison of current control techniques based on hysteresis and PI has been presented. Khrisna and Mohan [92], analysis of performance for vector controlled asynchronous machine with indirect vector-controlled techniques was proposed. Based to the variables of magnetic saturation that have been provided in [93], [94], the conventional current distribution approach usually provides the ideal d-axis current to build a stable flux linkage. The maximum torque per ampere (MTPA) technique is consider as an advanced vector control technique has been presented in [95], many nonlinear control techniques available such as control of neural network [96]-[100]. In Figure 6, The gaussian process-based current distribution approach was put out in [101]. This technique can produce high-performance output torque and increase the accuracy of synchronous machine current distribution [102]-[106]. Table 1 has provided a qualitative comparison between control techniques comparable studies in the literature, in addition to mentioning the advantages and disadvantages of each technique.

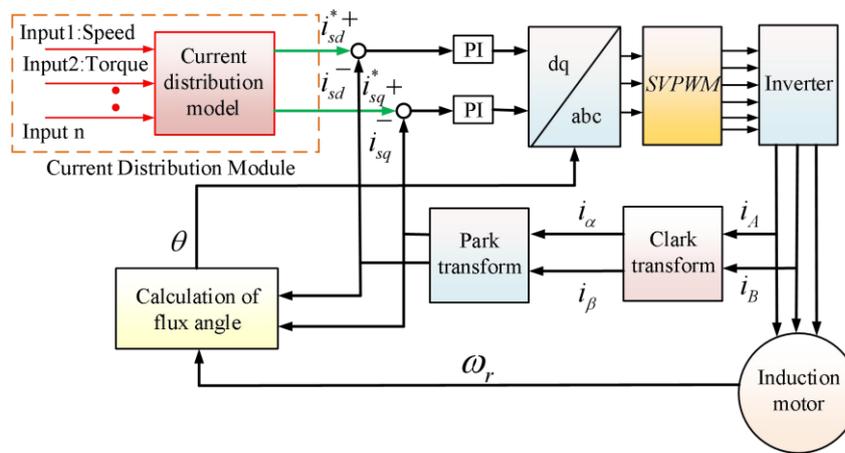


Figure 6. Current distribution model-based vector control

Table 1. A brief description of control methods

Research	Control approach	Positives	Drawbacks
Bhati and Yadav [16]	Direct torque control	faster torque response	Poor low-speed performance, parameter sensitivity, high torque, and flux ripples
Salahuddin <i>et al.</i> [22]	FM-PI, or fixed-mode proportional integral, speed controller	better performance when the time is rising	Not suitable for wide speed range control, steady-state error under nonlinearities
Sharma and Garg [34]	FOC, V/f	Simple implementation, low cost	Poor dynamic response, low accuracy
Allirani and Jagannathan [43]	DTC for voltage inverter	Torque and flux control independence, robustness	Variable switching frequency, Sensitivity to measurement errors
Goel <i>et al.</i> [53]	PI controller, DTC	Jaya optimization algorithm has been used for adjusting the speed PI controller’s gain parameters.	poor diversity control
Alexander <i>et al.</i> [61]	Indirect vector control	Fast dynamic response, suitable for wide speed range	slip calculation is needed, sensor requirement
Ansani and Deshpande [62]	Indirect vector control using and five level inverters	Lower harmonic distortion, better voltage utilization	Complex control and modulation, balancing DC link voltages
Silva and Araya [66]	Variable speed vector control	High efficiency, flexible operation, precision	Higher complexity, more difficult to implement
Jain <i>et al.</i> [72]	Multi-level inverter of vector control	Reduced motor stress, low harmonic distortion (THD)	Protection challenges, more hardware components
Arulmozhiyal <i>et al.</i> [90]	Scalar speed control using curve-fitting method	Flexibility, smoother performance, improved accuracy over linear V/f control	Parameter dependency, limited robustness, not suitable for high-performance drives
Wang <i>et al.</i> [94]	Vector control with constant Dc-link voltage	Better dynamic performance, reduced control burden	Reduced efficiency, higher switching harmonics at low speeds
Panchal <i>et al.</i> [103]	Distribution of current technique based on process gaussian	Torque optimization, predictive capability, reduced thermal stress	Complex implementation, computationally expensive

Nowadays, using of electric motors has become indispensable because they are used in so many different industrial applications. Unfortunately, the great majority of these motors are modest, with power outputs that don't go above a few kilowatts, and they usually have low efficiency (only 50%). This indicates that the motor does not turn half of its power into productive work. Since motor performance depends primarily on the control strategy used, new theories were suggested to control these motors, as in vector and scalar control. This study's significance stems from being able to provide the investor with a means to select the preferred control method to operate the motor with the highest possible efficiency.

According to above, the goal of this study is to improve a model uses scalar and vector control methods to drive a 3-phase squirrel cage induction motor. additionally to comparison between scalar and vector control to analyze performance of each system when operating the motor on a load with both constant and variable speeds, for using it in practical applications which depending on this kind of electric motor.

The results are so important because they offer a useful practical comparison between vector and scalar control of an asynchronous machine under actual variable-speed and bidirectional loading situations. The findings show that the choice of control approach has a direct impact on inverter performance, torque ripple, speed accuracy, and current stress. This provides engineers and researchers with precise guidelines for selecting suitable motor control methods based on cost and performance criteria. The simulation framework that has been given is also a helpful resource for future scholarly and business study.

**2. METHOD**

In this research, the method of driving a three-phase voltage inverter using the techniques of space vector modulation (SVM) and sinusoidal pulse width modulation (SPWM) has been explained, which later form the basis for two driving models based on vector control and scalar control respectively. The models have been created using the MATLAB/Simulink environment. In addition to creating a model representing a constant- and variable-speed load, which has been applied to the driven motor by using vector and scalar control methods, then performance of system has been compared in each case.

**2.1. Principle of scalar control**

When a three-phase induction motor is supplied with a constant voltage and frequency, it often operates as a constant-speed machine. Many industrial, scientific research, and electrical systems require controllable (variable speed) induction motors that can be driven by precisely adjusting their speeds. In recent years, as a result of the increase of hardware devices used in applications, the need to find mechanisms to drive induction motors according to the control parameters required in those applications has increased.

Scalar control is the control of only the amplitudes of the control variables, neglecting the effects of the interconnection between these variables in the induction machine. For example, by controlling the voltage amplitude, the flux can be controlled, and by controlling the frequency or slip, the torque can be controlled. Therefore, the control algorithm can be consider as controlling the motor by changing the frequency and voltage together while maintaining a constant rate of change ( $V/f = \text{constant}$ ), by supplying the motor with a voltage inverter that adopts the principle of SPWM.

Figure 7 has demonstrated the closed loop control used to drive a three-phase induction motor using the control principle  $V/f$ . The operating frequency has been determined based on the required speed and the rotational speed measured by the motor. PI controller has used to regulate the slip in order to maintain the motor speed at the desired value. Where the (1) has used to link the control variables flux  $\Phi$ , voltage  $V$ , angular frequency  $\omega$ .

$$\phi \approx \frac{V}{\omega} = \frac{1}{2\pi} \frac{V}{f} \tag{1}$$

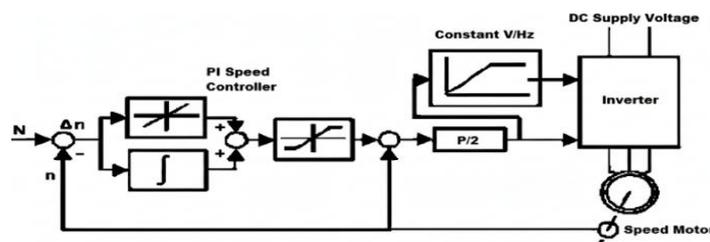


Figure 7. Closed loop control using control principle  $V/f$

The resulting frequency is used to determine the amplitude and angle of the voltage used in SPWM that will drive the inverter. Driving systems based on scalar control have some weaknesses in their performance, but they are easy to implement and are widely used in industrial applications. But it has become less important nowadays due to the superior performance of vector control-based driving systems required in most applications.

**2.1.1. Sinusoidal pulse width modulation (SPWM)**

The typical circuit of a three-phase voltage inveter that uses the pulse width modulation (PWM) principle is depicted in Figure 8. The output signal is formed by the six electronic switches, numbered S<sub>1</sub> through S<sub>6</sub>. Where it is driven using switching variables a, a', b, b', c, c'. When the upper transistors are closed (switched on) the values of a, b, c are all equal to 1. While the lower transistors are open (switched off) which means the values of a', b', c' are all equal to 0. Therefore, the open and close states of the upper transistor can be used to determine the output voltage. When applying the scalar control system, inverter has been driven by SPWM method.

**2.2. Principle of vector control**

The discovery of vector control dates back to early 1970, This method has been used to demonstrate that induction motors can be driven as if they were DC motors. Consequently, it offers good drive efficiency for induction motors. Vector control deals with the amplitude and phase angle of the motor's vector variables. It decouples both vector of stator and rotor current so they can be controlled separately, giving a fast response.

**2.2.1. Principle of pulse width modulation (PWM) using space vector modulation (SVM)**

SVM method is one of the most common SVM method used in modern drive system applications. The closed loop control that uses SVM to drive a three-phase induction motor can be seen in Figure 8. PWM using a space vector refers to a specific sequence of switching the upper transistor state of a three-phase voltage inverter. They are employed for more dependable utilization of the voltage source and to produce less distorted harmonics in the output voltages or in the currents delivered to the phases of an AC motor.

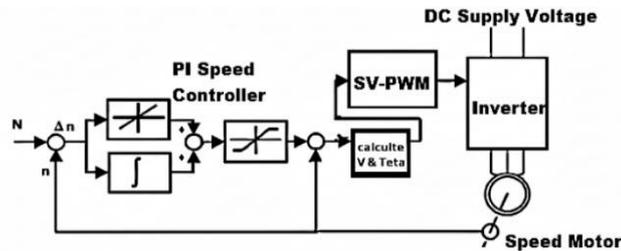


Figure 8. Closed loop control using SVM

In (2) and (3) have shown the relationship between the vector of the switching variable  $[a, b, c]^T$  and both the line voltage vector  $[V_{ab} V_{bc} V_{ca}]^T$  and the phase voltage vector  $[V_a V_b V_c]^T$  respectively:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3}$$

As shown in Figure 9, there are eight possible configurations for the open-close matrix of the upper electronic switches. Since the open and close states of the lower switches are exactly opposite to those of the upper switches, it will be easier to determine them after determining the state of the upper switches. Based on (2) and (3), we can find the octal switching vectors, the resulting phase voltages, and the resulting line voltages in terms of the DC supply voltage V<sub>dc</sub>.

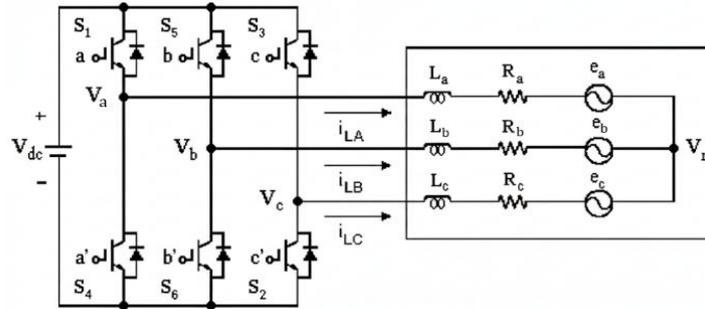


Figure 9. Three-phase voltage inverter uses PWM principle

where it is:

$$f_{dqo} = [f_d \ f_q \ f_o]^T$$

$$K_s = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

$$f_{abc} = [f_a \ f_b \ f_c]^T$$

where f refers to the voltage or current variable.

To apply PWM using space vector, the voltage equations in the reference system abc can be converted to the reference system of stator dq, which consists of the horizontal d and vertical q axes. Thus, the two referential statements have the following relationship:

$$f_{dqo} = K_s f_{abc} \tag{4}$$

The six non-zero vectors and the two zero vectors can be identified. Where the six non-zero vectors ( $V_1$ - $V_6$ ) form the hexagonal axes of the shape described in Figure 10, electrical power that feeds the load. The angle between any two adjacent vectors is non-zero ( $60^\circ$ ). While zero vectors ( $V_0$  and  $V_7$ ) are at coordinate origin. This results in applying zero voltage to the load. The eight vectors are called the primary space vectors that indicated as follows  $V_0, V_1, V_2, V_3, V_4, V_5, V_6,$  and  $V_7$ . The same transformation can be applied to the output voltage for obtaining the reference voltage vector  $V_{ref}$  in the d-q axes.

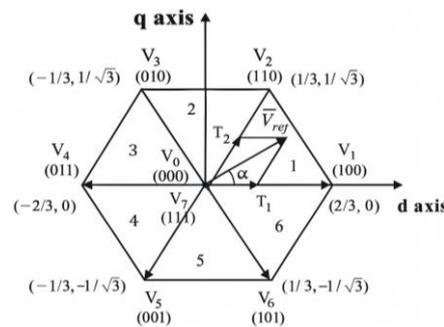


Figure 10. Basic switching vectors

### 3. RESULTS AND DISCUSSION

The research steps can be summed up by modeling the load at both fixed and variable speeds, describing the existing control models, and carefully examining how each system performs when the load is delivered to the motor.

#### 3.1. Modeling of fixed and variable speed load

An electric elevator drive system has been used to evaluate this study under both ascent (up) and descent(down) operating circumstances. The operating system can be divided into two stages:

**3.1.1. Ascent (up) stage**

Ascent (up) stage has represented motor operating condition in the first quadrant (positive rotation direction) which has been divided into three states according to (5) to achieve constant acceleration during take-off and stop. Figure 11 has shown the reference speed (N1) diagram for the ascent (1) diagram.

$$N1 = \begin{cases} 2400 * t & 0 < t \leq 0.5 \\ 1200 & 0.5 < t \leq 1.5 \\ -2400 * (t - 2) & 1.5 < t \leq 2 \end{cases} \tag{5}$$

Where N1 is reference speed in the ascent (up) stage, t represents time.

**3.1.2. Descent (down) stage**

Descent (down) stage has represented motor operating condition in the third quadrant (negative rotation direction) which has been divided into three states according to (6). Figure 12 has shown the reference speed (N2) diagram for the descent (down) stage.

$$N2 = \begin{cases} -2400 * t & 0 < t \leq 0.5 \\ -1200 & 0.5 < t \leq 1.5 \\ 2400 * (t - 2) & 1.5 < t \leq 2 \end{cases} \tag{6}$$

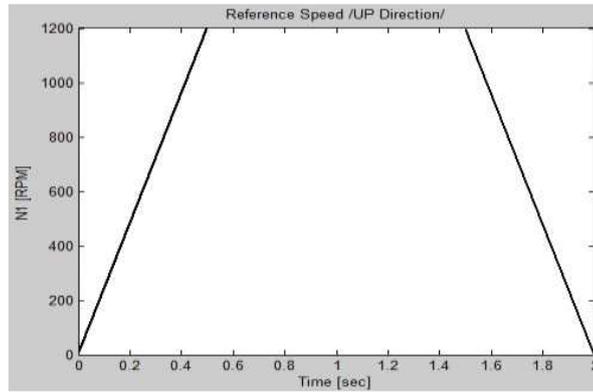


Figure 11. Reference speed (N1) diagram for the ascent (up) stage

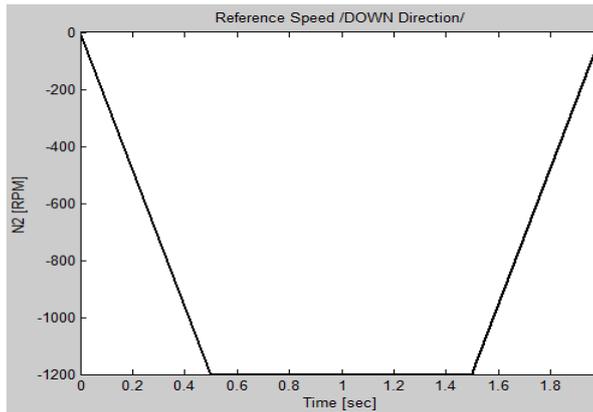


Figure 12. Reference speed (N2) diagram for the descent (down) stage

The findings demonstrate that the suggested load modeling effectively represents motor behavior during ascent and descent in operating at both fixed and variable speeds. Stable functioning under various load levels is made possible by the prescribed speed profiles, which guarantee smooth acceleration and deceleration. In all working quadrants, the control techniques provide dependable performance and efficient load handling.

3.2. Models of control utilized in the driving systems

3.2.1. Scalar control system

Figure 13 has illustrated the scalar control system in which the reference speed has been chosen to determine the operational state (up or down). In this system, the required operating frequency has been determined to rectify error between the intended (reference) speed and the actual speed by inputting the error signal to a proportional-integral (PI) controller a frequency signal limiter within the range (-50 ~ +50) Hz, the limiter's output signal has been integrated to generate the angular frequency signal ( $\omega t$ ) which allows to determine the three reference signals in the PWM system using a triangular signal of frequency 5 KHz which in generates the six control pulses to inverter that feed the induction motor.

3.2.2. Vector control system

Figure 14 has illustrated the vector control system in which the reference speed has been chosen to determine the operational state (up or down). In this system, the required operating frequency has been determined to rectify error between the intended (reference) speed and the actual speed by inputting the error signal to a PI controller a frequency signal limiter within the range (-50 ~ +50) Hz, The limiter's output signal has been integrated to generate the angular frequency signal ( $\omega t$ ) which allows to determine the signal of reference voltage (space vector) using in PWM system by modulating the space vector according to the modulation frequency 5 KHz which in generates the six control pulses to inverter that feed the induction motor.

3.3. Discussion of results

In the Table 2, parameters of 3-phase squirrel cage induction motor are listed.

Table 2. Parameters of induction motor

Description	Symbol	Value
Rated power	$P_n$	3 H.P
Rated voltage	$V_n$	380/220 V
Rated current	$I_n$	5.3/3.2 A
Rated speed	$N_n$	1420 r.p.m
Rotor inertia	$J$	0.023 kg.m <sup>2</sup>
Number of poles	$p$	2
Frequency	$f$	50 Hz
Inverter input voltage	$V_{DC}$	600 V
Loading torque	$T_L$	5 N.m
Stator resistance	$R_s$	0.435 $\Omega$ /ph
Rotor resistance (referred to stator)	$R_r$	0.816 $\Omega$ /ph
Inductance of stator leakage	$L_s$	4 mH
Inductance of rotor leakage (referred to stator)	$L_r$	2 mH
Inductance of magnetizing (referred to stator)	$L_m$	69.31 mH

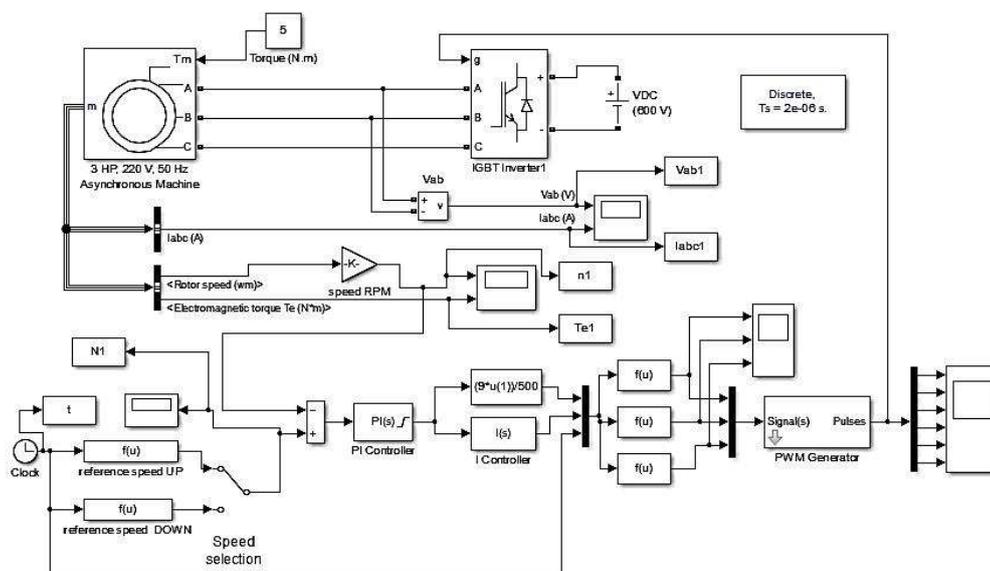


Figure 13. Model of scalar control system

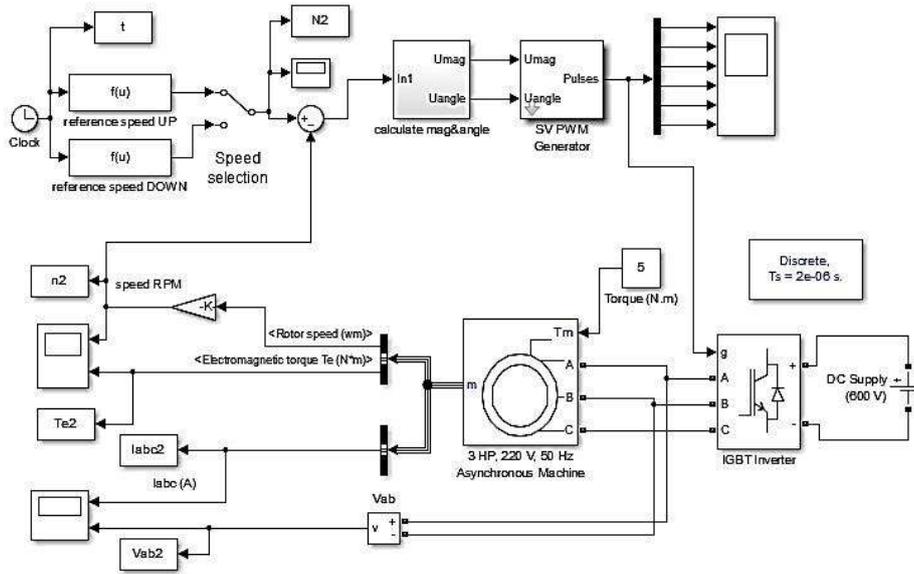


Figure 14. Model of vector control system

**3.3.1. Ascent (up) stage**

Figure 15 has shown the speed curve of the two control systems (scalar-vector) ascent (up) stage. The scalar control system's curve, shown by curve n<sub>1</sub>, indicates that the maximum error value occurred in the situation of acceleration after starting, at speed (500 r.p.m) and at times (0.23 sec) and (0.27 sec). While the maximum speed error value in the case of fixed speed was 10 r.p.m., which occurred at time (0.8 sec). However, the value of this error in the case of slowing down before stopping was (100 r.p.m), that occurred at time (1.77 sec). Regarding the vector control system's curve, represented by curve n<sub>2</sub>, it was found that the maximum speed error value (in all cases) was (2 r.p.m), which is a very small value in comparison to the values obtained by using the scalar control method. This indicates that the vector control method performs better than the scalar control method.

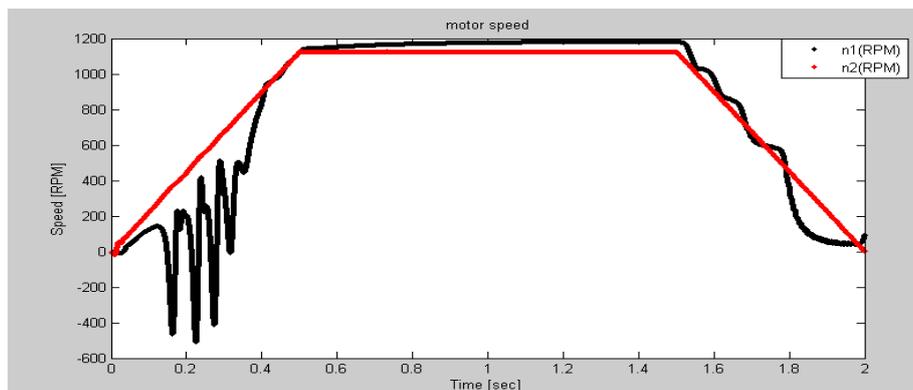


Figure 15. Motor speed in vector and scalar control systems during ascent (up) stage

Figure 16 has shown the electromagnetic torque curve of the two control systems (scalar-vector) ascent (up) stage. It is obvious that bumps appear in the torque curve T<sub>e1</sub> resulting from the scalar control system, which reached very high values, exceeding (2500 N.m) in some times. which caused arising high currents, as seen by the curve I<sub>abc1</sub> in Figure 17, occasionally exceeding (200 A). while in the torque curve T<sub>e2</sub> resulting from the vector control system as we can see in Figure 16. It should be noted that the torque fluctuates within reasonable bounds and never rises above (20 N.m). The currents resulting from these torques, as shown in Figure 17, which represented by the curve I<sub>abc2</sub>, are in acceptable transient cases not surpassing the value (50A) for a very short period of time, then return to the value of (15A).

When such values arise for both torque and transient currents in a scalar control system, the efficiency of the system decreases due to the higher losses. Additionally, it impairs performance by raising the temperature of the electronic switches and equipment, which might result in their collapse when the allowable limit values are above. Economically speaking, it is detrimental since electronic switches that can manage these high currents must be bought. Consequently, vector control outperforms scalar control with regard to of electrical switch performance, efficiency, and cost.

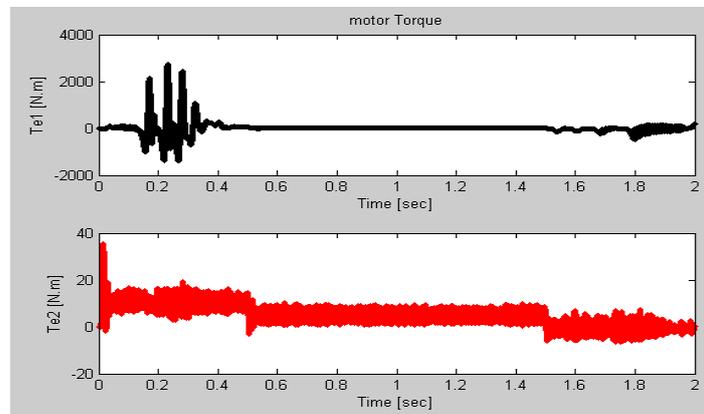


Figure 16. Electromagnetic torque for motor in vector and scalar control systems during ascent (up) stage

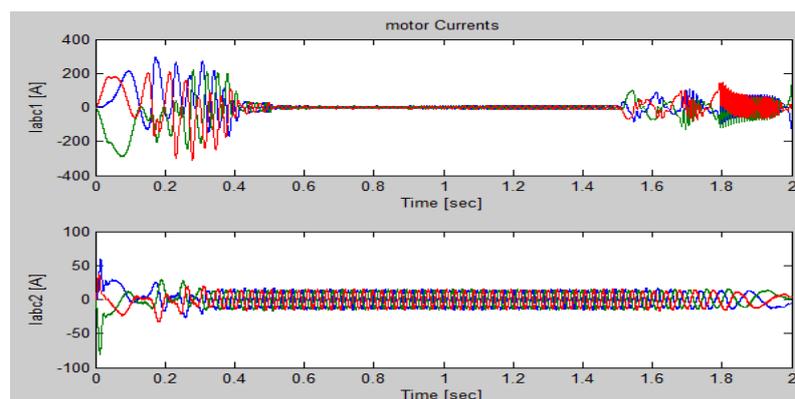


Figure 17. Stator current for motor in vector and scalar control systems during ascent (up) stage

**3.3.2. Descent (down) stage**

Figure 18 has shown the speed curve of the two control systems (scalar-vector) descent (down) stage (in other words, when the motor rotates in the opposite direction). The scalar control system’s curve, shown by curve  $n_3$ , several maximum values of speed error are demonstrated with high limits. This error in the curve  $n_4$  from the vector control system was very small compared to the values from the scalar control system, demonstrating the superiority of the vector control system when the motor operates at the same load and in the opposite direction.

Figure 19 has shown the electromagnetic torque curve of the two control systems (scalar-vector) descent (down) stage. It is obvious that the scalar control system caused bumps in the torque curve  $T_{e3}$ , which sometimes reached very high values. Which caused arising high currents, as seen by the curve  $I_{abc3}$  in Figure 20, occasionally exceeding (250 A) whereas Figure 19 has shown the torque curve  $T_{e4}$  obtained from the vector control system. It should be mentioned that the torque fluctuates within acceptable ranges, as seen in Figure 20, the currents resulting from these torques are in allowable temporary scenarios, as indicated by the curve  $I_{abc4}$ . After analyzing the load ascent and descent scenarios, we conclude that the vector control system is superior to the scalar control system in regards to performance, efficiency, and the cost of the inverter’s electronic switches, in contrast, the scalar control system’s economic cost is offset because it does not require a controller to generate control pulses to the inverter. Practical applications that need for independent torque and speed control as well as increased output signal stability can make use of the vector control system.

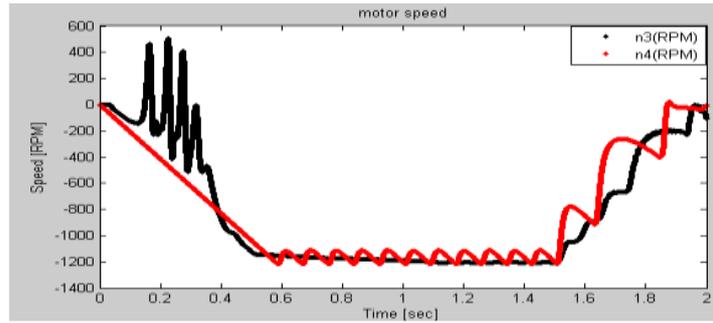


Figure 18. Motor speed in vector and scalar control systems during descent (down) stage

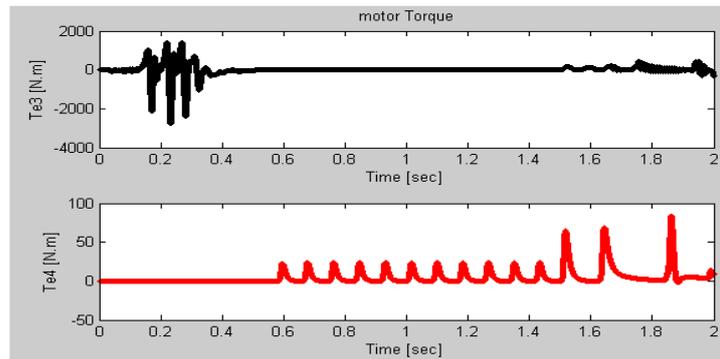


Figure 19. Electromagnetic torque for motor in vector and scalar control systems during descent (down) stage

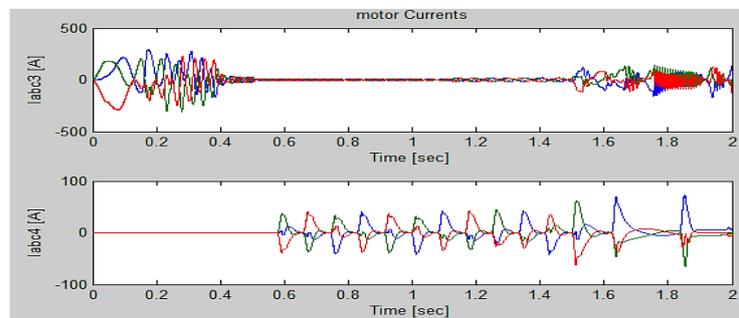


Figure 20. Stator current for motor in vector and scalar control systems during descent (down) stage

The findings demonstrate that during both the ascending and descent phases, vector control performs noticeably better than scalar control. Vector control ensures steady operation in both rotation directions by achieving far lower speed errors, a smoother torque response, and significantly fewer current peaks. Scalar control, on the other hand, results in significant torque and current changes, which raise losses, thermal stress, and inverter cost. All things considered, vector control offers better performance, efficiency, and dependability, which makes it more appropriate for applications needing exact torque and speed management.

The results are so important because they offer a useful practical comparison between scalar and vector control of a three-phase induction motor under actual variable-speed and bidirectional loading situations. The findings show that the choice of control approach has a direct impact on inverter performance, torque ripple, speed accuracy, and current stress. This provides engineers and researchers with precise guidelines for selecting suitable motor control methods based on cost and performance criteria. The simulation framework that has been given is also a helpful resource for future scholarly and business study. According to above, it is evident that the vector control method outperforms the scalar control method by a wide margin. Table 3 has shown simple comparison between vector control and scalar control method.

Table 3. Simple comparison between vector control and scalar control method

Scalar control method	Vector control method
Simple	Complex
Slow response	Fast response
Low-cost technique	High-cost technique
Low performance in speed regulation	Speed regulation is excellent

#### 4. CONCLUSION

The study proves to the conclusion that for three-phase induction motors to operate efficiently, vector control provides a notable performance benefit over scalar control. The primary characteristic of vector control is its capacity to dissociate torque and flux, which enables autonomous and accurate control of motor dynamics and improves performance across crucial parameters including response time, torque control, and harmonic distortion. Advanced PWM techniques are incorporated into vector control to further improve its abilities to reduce harmonics, maximize power efficiency, and provide quick, dynamic responses. These features make vector control ideal for applications like robotics, and high-performance industrial drives where high precision, quick speed response, and low harmonic content are necessary.

For simpler applications with less demanding requirements for high performance, scalar control is still a practical and affordable option. Scalar control offers a suitable and useful solution for use cases where low cost, simplicity, and convenience of implementation are more important than accurate control, such as in fans, pumps. It is easier to build since it relies on the more straightforward voltage-to-frequency (V/f) approach. Especially in cases where dynamic torque adjustment and great accuracy are not necessary. Therefore, the specific demands of the application should determine whether to use scalar or vector control, taking into account variables like cost, performance requirements and complexity.

Scalar control's simplicity makes it perfect for less demanding contexts, even though vector control is clearly the more advanced and potent method. These techniques can improve system performance and efficiency by increasing adaptability and optimizing control strategies in real-time. Future research can build on this study by using advanced control techniques to improve resilience and dynamic performance under changing load situations. For useful industrial applications, sensorless control and energy-efficiency improvement can also be investigated.

#### REFERENCES

- [1] G. Cimuca, S. Breban, M. M. Radulescu, C. Saudemont, and B. Robyns, "Design and control strategies of an induction-machine-based flywheel energy storage system associated to a variable-speed wind generator," *IEEE Transactions on Energy Conversion*, vol. 25, no. 2, pp. 526–534, Jun. 2010, doi: 10.1109/tec.2010.2045925.
- [2] S. Jurkovic, K. M. Rahman, J. C. Morgante, and P. J. Savagian, "Induction machine design and analysis for general motors e-assist electrification technology," *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 631–639, Jan. 2015, doi: 10.1109/tia.2014.2330057.
- [3] H. Sarde, A. Auti, and V. Gadhav, "Speed control of induction motor using vector control technique," *International Journal of Engineering Research*, vol. 3, no. 4, pp. 1–6, 2014.
- [4] P. Aree, "Analytical approach to determine speed-torque curve of induction motor from manufacturer data," *Procedia Computer Science*, vol. 86, pp. 293–296, 2016, doi: 10.1016/j.procs.2016.05.076.
- [5] X. Sun, Z. Shi, G. Lei, Y. Guo, and J. Zhu, "Analysis and design optimization of a permanent magnet synchronous motor for a campus patrol electric vehicle," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 11, pp. 10535–10544, Nov. 2019, doi: 10.1109/tvt.2019.2939794.
- [6] X. Sun, K. Diao, G. Lei, Y. Guo, and J. Zhu, "Real-time HIL emulation for a segmented-rotor switched reluctance motor using a new magnetic equivalent circuit," *IEEE Transactions on Power Electronics*, vol. 35, no. 4, pp. 3841–3849, Apr. 2020, doi: 10.1109/tpel.2019.2933664.
- [7] X. Sun, Y. Shen, S. Wang, G. Lei, Z. Yang, and S. Han, "Core losses analysis of a novel 16/10 segmented rotor switched reluctance BSG motor for HEVs using nonlinear lumped parameter equivalent circuit model," *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 2, pp. 747–757, Apr. 2018, doi: 10.1109/tmech.2018.2803148.
- [8] Z. Dong, Y. Yu, W. Li, B. Wang, and D. Xu, "Flux-weakening control for induction motor in voltage extension region: torque analysis and dynamic performance improvement," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 5, pp. 3740–3751, May 2018, doi: 10.1109/tie.2017.2764853.
- [9] O. Al-Abad Al-khamis and A. A. Safe, "Study of induction generators performance of two-speed used in standalone wind turbines," *International Journal of Energy and Smart Grid*, vol. 1, no. 2, pp. 37–57, Dec. 2016, doi: 10.23884/ijesg.2016.1.2.02.
- [10] A. K. Swain and S. K. Senapati, "An experimental investigation of self-excitation in stand-alone induction generator," in *2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014]*, Mar. 2014, pp. 245–249, doi: 10.1109/iccpct.2014.7054906.
- [11] Y. Wang, T. Ito, and R. D. Lorenz, "Loss manipulation capabilities of deadbeat direct torque and flux control induction machine drives," *IEEE Transactions on Industry Applications*, vol. 51, no. 6, pp. 4554–4566, Nov. 2015, doi: 10.1109/tia.2015.2455030.
- [12] S. Patel, "Speed control of three phase induction motor using variable frequency drive," *California State University, Long Beach*, 2018.

- [13] G. Von Pflingsten, S. Steentjes, and K. Hameyer, "Operating point resolved loss calculation approach in saturated induction machines," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 3, pp. 2538–2546, Mar. 2017, doi: 10.1109/tie.2016.2597761.
- [14] M. Centner and U. Schafer, "Optimized design of high-speed induction motors in respect of the electrical steel grade," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 1, pp. 288–295, Jan. 2010, doi: 10.1109/tie.2009.2029523.
- [15] D. Casadei, F. Profumo, G. Serra, and A. Tani, "FOC and DTC: two viable schemes for induction motors torque control," *IEEE Transactions on Power Electronics*, vol. 17, no. 5, pp. 779–787, Sep. 2002, doi: 10.1109/tpel.2002.802183.
- [16] R. Bhati and V. K. Yadav, "Direct torque control of induction motor drive fed by VSI: modeling and simulation," *International Journal of Technical Research & Science*, vol. 8, no. 09, pp. 1–7, Sep. 2023, doi: 10.30780/ijtrs.v08.i09.001.
- [17] J. W. Finch and D. Giaouris, "Controlled AC electrical drives," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 2, pp. 481–491, 2008, doi: 10.1109/tie.2007.911209.
- [18] K. Sundararaju, R. S. Kumar, and I. G. C. Raj, "Modeling and simulation of neural based speed controller for direct torque control of three phase induction motor," in *TENCON 2017 - 2017 IEEE Region 10 Conference*, Nov. 2017, pp. 1439–1444, doi: 10.1109/tencon.2017.8228084.
- [19] S. Hegde, S. Angadi, and A. B. Raju, "Speed control of 3-phase induction motor using volt/hertz control for automotive application," in *2016 International Conference on Circuits, Controls, Communications and Computing (I4C)*, Oct. 2016, pp. 1–5, doi: 10.1109/cimca.2016.8053311.
- [20] M. R. B. Fathima and S. R. Prasath, "Mathematical modeling of SVPWM inverter fed 3 phase induction motor vector control in MATLAB/Simulink environment," in *2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, Apr. 2017, pp. 1–8, doi: 10.1109/iccpct.2017.8074205.
- [21] G. Kohlrusz and D. Fodor, "Comparison of scalar and vector control strategies of induction motors," *Hungarian Journal of Industry and Chemistry*, vol. 39, no. 2, pp. 265–270, 2011.
- [22] H. Salahuddin *et al.*, "Electric vehicle transient speed control based on vector control FM-PI speed controller for induction motor," *Applied Sciences*, vol. 12, no. 17, p. 8694, Aug. 2022, doi: 10.3390/app12178694.
- [23] D. Ganga and V. Ramachandran, "IoT-based vibration analytics of electrical machines," *IEEE Internet of Things Journal*, vol. 5, no. 6, pp. 4538–4549, Dec. 2018, doi: 10.1109/jiot.2018.2835724.
- [24] R. Krishnan, "Electric motor drives – modeling, analysis and control," *Pearson Prentice Hall*, 2013.
- [25] H. M. Karkar, "Improvement speed regulation in open loop V/F control of three phase induction motor drive," *IJDI-ERET*, pp. 52–58, 2013.
- [26] H. Mikhael, H. Jalil, and I. Ibrahim, "Speed control of induction motor using PI and V/F scalar vector controllers," *International Journal of Computer Applications*, vol. 151, no. 7, pp. 36–43, Oct. 2016, doi: 10.5120/ijca2016911831.
- [27] A. Consoli, G. Scelba, G. Scarcella, and M. Cacciato, "New scalar control for full speed operating range IM drives," in *2011 IEEE International Electric Machines & Drives Conference (IEMDC)*, May 2011, pp. 170–175.
- [28] P. K. Behra, M. K. Behra, and A. K. Sahoo, "Speed control of induction motor using scalar control," *International Journal of Computer Applications*, vol. 975, 2014.
- [29] S. Mehto and R. S. Lodhi, "Comparison and analysis of total harmonic distortion for IGBT and MOSFET based VS inverter," *IOSR Journal of Electrical and Electronics Engineering*, vol. 9, no. 3, pp. 62–66, 2014, doi: 10.9790/1676-09356266.
- [30] A. Agrawal, R. S. Lodhi, and P. Nema, "Comparison between scalar and vector control technique for induction motor drive," *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, no. 6, pp. 2504–2509, 2018.
- [31] A. M. Hava and N. O. Çetin, "A generalized scalar PWM approach with easy implementation features for three-phase, three-wire voltage-source inverters," *IEEE Transactions on Power Electronics*, vol. 26, no. 5, pp. 1385–1395, May 2011, doi: 10.1109/tpel.2010.2081689.
- [32] E. M. Hussein, M. E. Shalaby, H. A. M. Shatla, A. Refky, "Speed control of a three phase induction motor using field oriented control," *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, vol. 2, no. 11, pp. 3212–3220, 2015.
- [33] I. M. Alsofyani and N. R. N. Idris, "A review on sensorless techniques for sustainable reliability and efficient variable frequency drives of induction motors," *Renewable and Sustainable Energy Reviews*, vol. 24, pp. 111–121, Aug. 2013, doi: 10.1016/j.rser.2013.03.051.
- [34] N. Sharma and V. K. Garg, "A comparative analysis of scalar and vector control of induction motor drive," *Impending Power Demand and Innovative Energy*, pp. 230–242, 2013.
- [35] C. D. Tran, P. Brandstetter, M. H. C. Nguyen, S. D. Ho, P. N. Pham, and B. H. Dinh, "An improved current-sensorless method for induction motor drives applying hysteresis current controller," *Indonesian Journal of Electrical Engineering and Informatics (IJEI)*, vol. 9, no. 1, Jan. 2021, doi: 10.52549/ijeii.v9i1.1619.
- [36] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of PWM inverter-Fed AC motors—a survey," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 4, pp. 744–757, Aug. 2004, doi: 10.1109/tie.2004.831717.
- [37] Aditya, "Simulink model of direct torque control of induction machine," *American Journal of Applied Sciences*, vol. 5, no. 8, pp. 1083–1090, Aug. 2008, doi: 10.3844/ajassp.2008.1083.1090.
- [38] J. H. Ryu, K. W. Lee, and J. S. Lee, "A unified flux and torque control method for DTC-based induction-motor drives," *IEEE Transactions on Power Electronics*, vol. 21, no. 1, pp. 234–242, Jan. 2006, doi: 10.1109/tpel.2005.861176.
- [39] M. Mengoni, L. Zarri, A. Tani, G. Serra, and D. Casadei, "Stator flux vector control of induction motor drive in the field weakening region," *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 941–949, Mar. 2008, doi: 10.1109/tpel.2007.915636.
- [40] Z. Zhang, R. Tang, B. Bai, and D. Xie, "Novel direct torque control based on space vector modulation with adaptive stator flux observer for induction motors," *IEEE Transactions on Magnetics*, vol. 46, no. 8, pp. 3133–3136, Aug. 2010, doi: 10.1109/tmag.2010.2051142.
- [41] Y. S. K. Babu, G. T. R. Das, "Improvement in direct torque control of induction motor using fuzzy logic duty ratio controller," *ARN Journal of Engineering and Applied Sciences*, vol. 5, no. 4, pp. 68–73, 2010.
- [42] S. K. Sahoo, G. K. R. Das, V. Subrahmanyam, "VLSI design approach to high-performance direct torque control of induction motor drives," *World Journal of Modelling and Simulation*, vol. 4, no. 5, pp. 269–276, 2008.
- [43] S. Allirani, V. Jagannathan, "Direct torque control technique for voltage source inverter fed induction motor drive," *International Journal of Electrical Engineering*, vol. 5, no. 5, pp. 629–640, 2012.
- [44] N. Rajasekar and K. M. Sundaram, "Feedback controller design for variable voltage variable speed induction motor drive via ant colony optimization," *Applied Soft Computing*, vol. 12, no. 8, pp. 2132–2136, Aug. 2012, doi: 10.1016/j.asoc.2012.03.012.

- [45] M. Najeeb, H. Daniyal, R. Razali, and M. Mansor, "An efficient control implementation for inverter based harmony search algorithm," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 8, no. 1, p. 279, Mar. 2017, doi: 10.11591/ijpeds.v8.i1.pp279-289.
- [46] O. Roeva and T. Slavov, "Firefly algorithm tuning of PID controller for glucose concentration control during E. coli Fed-batch cultivation process," *Proceedings of the Federated Conference on Computer Science and Information Systems*, pp. 455–462, 2012.
- [47] Kuppasamy, "Genetic algorithm based proportional integral controller design for induction motor," *Journal of Computer Science*, vol. 7, no. 3, pp. 416–420, Mar. 2011, doi: 10.3844/jcssp.2011.416.420.
- [48] M. M. Eissa, G. S. Virk, A. M. AbdelGhany, and E. S. Ghith, "Optimum induction motor speed control technique using genetic algorithm," *American Journal of Intelligent Systems*, vol. 3, no. 1, pp. 1–12, 2013.
- [49] P. Brandstetter and M. Dobrovsky, "Speed control of A.C. drive with induction motor using genetic algorithm," in *International Joint Conference CISIS '12-ICEUTE '12-SOCO '12 Special Sessions*, Springer Berlin Heidelberg, 2013, pp. 341–350.
- [50] R. Essakiraj, "Speed control of induction machines using GA based PID controller," *Middle-East Journal of Scientific Research*, vol. 23, pp. 164–169, 2015.
- [51] S. S. Rao and T. V. Kumar, "Direct torque control of induction motor drives for optimum stator flux and torque ripple," in *2011 IEEE Ninth International Conference on Power Electronics and Drive Systems*, Dec. 2011, pp. 952–955, doi: 10.1109/peds.2011.6147370.
- [52] Y. Singh, "Genetic algorithms: concepts, design for optimization of process controllers," *Computer and Information Science*, vol. 4, no. 2, pp. 39–54, 2011.
- [53] N. Goel, S. Chacko, and R. N. Patel, "A parameter less stochastic optimization technique for tuning of speed PI controller of DTC induction motor drive," *IAES International Journal of Robotics and Automation (IJRA)*, vol. 8, no. 2, p. 105, Jun. 2019, doi: 10.11591/ijra.v8i2.pp105-112.
- [54] R. Abebe, M. Di Nardo, D. Gerada, G. Lo Calzo, L. Papini, and C. Gerada, "High speed drives review: Machines, converters and applications," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2016, pp. 1675–1679, doi: 10.1109/iecon.2016.7793721.
- [55] M. Shankar, "Scalar and vector controlled inverter topology FED three phase induction motor," *International Journal of Scientific Research and Engineering Trends*, vol. 10, no. 5, pp. 1792–1797, Jul. 2024, doi: 10.61137/ijstet.vol.10.issue5.230.
- [56] G. Buja and R. Menis, "Steady-state performance degradation of a DTC IM drive under parameter and transduction errors," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1749–1760, Apr. 2008, doi: 10.1109/tie.2008.917112.
- [57] A. Jidin, N. R. N. Idris, A. H. M. Yatim, T. Sutikno, and M. E. Elbuluk, "An optimized switching strategy for quick dynamic torque control in DTC-hysteresis-based induction machines," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 8, pp. 3391–3400, Aug. 2011, doi: 10.1109/tie.2010.2087299.
- [58] Y. Sangsefidi, S. Ziaeinejad, and A. Shoulaie, "A simple and low-cost method for three-phase induction motor control in high-speed applications," in *2012 3rd Power Electronics and Drive Systems Technology (PEDSTC)*, Feb. 2012, pp. 212–217, doi: 10.1109/pedstc.2012.6183327.
- [59] B. K. Bose, "Modern power electronics and AC drives," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 2, pp. 581–588, 2008.
- [60] R. S. Lodhi and P. Thakur, "Performance and comparison analysis of indirect vector control of three phase induction motor," *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 10, pp. 716–724, 2013.
- [61] Alexander, S. Albert, T. Manigandan, M. D. Kumar, and R. V. Vardhan, "A comparison of simulation tools for power electronics," in *Proceedings of International Simulation Conference, ISCI*, 2012.
- [62] A. Ansari and D. M. Deshpande, "Mathematical model of asynchronous machine in MATLAB Simulink," *International Journal of Engineering Science and Technology*, vol. 2, no. 5, pp. 1260–1267, 2010.
- [63] W. I. Ibrahim, M. T. Raja, Ismail, and M. R. G. Ali, "Development of variable speed drive for single phase induction motor based on frequency control," *4th Engineering Conference*, 2011.
- [64] A. Emil Hasan, H. Hassan, and I. Bugis, "Variable speed vector control for induction motor of electric vehicle," *Applied Mechanics and Materials*, vol. 699, pp. 759–764, Nov. 2014, doi: 10.4028/www.scientific.net/amm.699.759.
- [65] W. Khoury, A. Nasser, and P. T. Szemes, "Three phase induction motor modelling and control using vector control in LabVIEW," *ANNALS OF THE ORADEA UNIVERSITY. Fascicle of Management and Technological Engineering.*, vol. XXVII (XVII), 2018/1, no. 1, 2018, doi: 10.15660/auofmte.2018-1.3344.
- [66] C. Silva and R. Araya, "Sensorless vector control of induction machine with low speed capability using MRAS with drift and inverter nonlinearities compensation," in *EUROCON 2007 - The International Conference on "Computer as a Tool," 2007*, pp. 1922–1928, doi: 10.1109/eurcon.2007.4400662.
- [67] S. Shukla and B. Singh, "Single-stage PV array fed speed sensorless vector control of induction motor drive for water pumping," *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3575–3585, Jul. 2018, doi: 10.1109/tia.2018.2810263.
- [68] T. Fukumoto, Y. Kato, K. Kurita, and Y. Hayashi, "Performance improvement of induction motor speed sensor-less vector control system using an adaptive observer with an estimated flux feedback in low-speed range," *Electrical Engineering in Japan*, vol. 169, no. 3, pp. 33–46, Jul. 2009, doi: 10.1002/ej.20909.
- [69] A. S. A. Mohamed, A. Gopinath, and M. R. Baiju, "A simple space vector PWM generation scheme for any general  $n$ -level inverter," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 5, pp. 1649–1656, May 2009, doi: 10.1109/tie.2008.2011337.
- [70] G. Durgasukumar and M. K. Pathak, "Indirect vector control induction motor drive performance under low speed," *Journal of Electrical Systems*, vol. 8, no. 3, pp. 338–347, 2012.
- [71] H. Abu-Rub, A. Iqbal, and J. Guzinski, *High performance control of AC drives with MATLAB®/Simulink*. Wiley, 2021.
- [72] J. K. Jain, S. Ghosh, S. Maity, and P. Dworak, "PI controller design for indirect vector controlled induction motor: a decoupling approach," *ISA Transactions*, vol. 70, pp. 378–388, Sep. 2017, doi: 10.1016/j.isatra.2017.05.016.
- [73] H. H. Ammar, A. T. Azar, T. D. Tembi, K. Tony, and A. Sosa, "Design and implementation of fuzzy PID controller into multi agent smart library system prototype," in *The International Conference on Advanced Machine Learning Technologies and Applications (AMLTA2018)*, Springer International Publishing, 2018, pp. 127–137.
- [74] K. Wang, R. D. Lorenz, and N. A. Baloch, "Improvement of back-EMF self-sensing for induction machines when using deadbeat-direct torque and flux control," *IEEE Transactions on Industry Applications*, vol. 53, no. 5, pp. 4569–4578, Sep. 2017, doi: 10.1109/tia.2017.2711964.
- [75] Y. Zhang, Z. Yin, and G. Li, "A novel speed estimation method of induction motors using real-time adaptive extended Kalman filter," *Journal of Electrical Engineering and Technology*, vol. 13, no. 1, pp. 287–297, 2018.
- [76] Z. Xin, R. Zhao, F. Blaabjerg, L. Zhang, and P. C. Loh, "An improved flux observer for field-oriented control of induction motors based on dual second-order generalized integrator frequency-locked loop," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 1, pp. 513–525, Mar. 2017, doi: 10.1109/jestpe.2016.2623668.

- [77] Z. Zhou, J. Yu, H. Yu, and C. Lin, "Neural network-based discrete-time command filtered adaptive position tracking control for induction motors via backstepping," *Neurocomputing*, vol. 260, pp. 203–210, Oct. 2017, doi: 10.1016/j.neucom.2017.04.032.
- [78] N. Wang, H. Yu, and X. Liu, "DTC of induction motor based on adaptive sliding mode control," in *2018 Chinese Control And Decision Conference (CCDC)*, Jun. 2018, pp. 4030–4034, doi: 10.1109/ccdc.2018.8407823.
- [79] F. Lftisi and M. A. Rahman, "A novel finite element controller map for intelligent control of induction motors," in *2017 8th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, Oct. 2017, pp. 18–24, doi: 10.1109/iemcon.2017.8117131.
- [80] Y. Feng, M. Zhou, F. Han, and X. Yu, "Speed control of induction motor servo drives using terminal sliding-mode controller," in *Advances in Variable Structure Systems and Sliding Mode Control—Theory and Applications*, Springer International Publishing, 2017, pp. 341–356.
- [81] Y. Guo, X. Wang, Y. Guo, and W. Deng, "Speed-sensorless direct torque control scheme for matrix converter driven induction motor," *The Journal of Engineering*, vol. 2018, no. 13, pp. 432–437, Jan. 2018, doi: 10.1049/joe.2018.0016.
- [82] A. Khlaief, O. Saadaoui, M. Abassi, A. Chaari, and M. Boussak, "Open circuit fault detection and FTC for sensorless PMS motor control based on the back-EMF SMO," *International Journal of Electronics*, vol. 108, no. 2, pp. 264–283, Jul. 2020, doi: 10.1080/00207217.2020.1793399.
- [83] K. Sharma, A. Agrawal, and S. Bandopadhaya, "Fuzzy logic controlled variable frequency drives," in *Harmony Search and Nature Inspired Optimization Algorithms*, Springer Singapore, 2018, pp. 1153–1164.
- [84] J. Pongfai and W. Assawinchaichote, "Optimal PID parametric auto-adjustment for BLDC motor control systems based on artificial intelligence," in *2017 International Electrical Engineering Congress (iEECON)*, Mar. 2017, pp. 1–4, doi: 10.1109/ieecon.2017.8075892.
- [85] Ö. Otkun, "Newton–Raphson based scalar speed control and optimization of IM," *Automatika*, vol. 62, no. 1, pp. 55–64, Nov. 2020, doi: 10.1080/00051144.2020.1846322.
- [86] Ö. Otkun, "İndüksiyon motor denetiminde interpolasyon tekniklerinin Kull animi," *Pamuk kale Üniversitesi, Mühendislik Bilimleri Dergisi*, vol. 26, no. 2, pp. 301–311, 2020.
- [87] A. Khitrov, A. Khitrov, and K. Kurnikov, "Parameter identification of induction motor drives," in *2021 28th International Workshop on Electric Drives: Improving Reliability of Electric Drives (IWED)*, Jan. 2021, pp. 1–5, doi: 10.1109/iwed52055.2021.9376382.
- [88] Ö. Otkun, F. Demir, and S. Otkun, "Scalar speed control of induction motor with curve-fitting method," *Automatika*, vol. 63, no. 4, pp. 618–626, Apr. 2022, doi: 10.1080/00051144.2022.2060657.
- [89] K. S. Gaeid, H. W. Ping, and H. A. F. Mohamed, "Indirect vector control of a variable frequency induction motor drive (VCIMD)," in *International Conference on Instrumentation, Communication, Information Technology, and Biomedical Engineering 2009*, Nov. 2009, pp. 36–40, doi: 10.1109/icici-bme.2009.5417273.
- [90] R. Arulmozhiyal, K. Baskaran, and R. Manikandan, "An intelligent speed controller for indirect vector controlled induction motor drive," in *2010 IEEE International Conference on Computational Intelligence and Computing Research*, Dec. 2010, pp. 1–5, doi: 10.1109/iccic.2010.5705816.
- [91] D. G. Holmes, B. P. McGrath, and S. G. Parker, "Current regulation strategies for vector-controlled induction motor drives," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 10, pp. 3680–3689, Oct. 2012, doi: 10.1109/tie.2011.2165455.
- [92] Krishna and S. Mohan, "Vector controlled induction motor drive with constant DC-Link voltage," *International Journal of Electrical and Electronics Engineering Research (IJEEER)*, vol. 3, no. 1, pp. 221–230, 2013.
- [93] X.-H. Jin, Y. Zhang, and D.-G. Xu, "Static current error elimination algorithm for induction motor predictive current control," *IEEE Access*, vol. 5, pp. 15250–15259, 2017, doi: 10.1109/access.2017.2725269.
- [94] M.-Y. Wang, R. Yang, Q. Tan, J.-W. Cao, C.-M. Zhang, and L.-Y. Li, "A high-bandwidth and strong robust current control strategy for PMLSM drives," *IEEE Access*, vol. 6, pp. 40929–40939, 2018, doi: 10.1109/access.2018.2857458.
- [95] S. Bozhko, S. Dymko, S. Kovbasa, and S. M. Peresada, "Maximum torque-per-amp control for traction IM drives: theory and experimental results," *IEEE Transactions on Industry Applications*, vol. 53, no. 1, pp. 181–193, Jan. 2017, doi: 10.1109/tia.2016.2608789.
- [96] X. Sun, Z. Shi, L. Chen, and Z. Yang, "Internal model control for a bearingless permanent magnet synchronous motor based on inverse system method," *IEEE Transactions on Energy Conversion*, vol. 31, no. 4, pp. 1539–1548, Dec. 2016, doi: 10.1109/tec.2016.2591925.
- [97] X. Sun, L. Chen, Z. Yang, and H. Zhu, "Speed-sensorless vector control of a bearingless induction motor with artificial neural network inverse speed observer," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 4, pp. 1357–1366, Aug. 2013, doi: 10.1109/tmech.2012.2202123.
- [98] X. Sun et al., "MPTC for PMSMs of EVs with multi-motor driven system considering optimal energy allocation," *IEEE Transactions on Magnetics*, vol. 55, no. 7, pp. 1–6, Jul. 2019, doi: 10.1109/tmag.2019.2904289.
- [99] X. Sun, C. Hu, G. Lei, Y. Guo, and J. Zhu, "State feedback control for a PM hub motor based on gray wolf optimization algorithm," *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 1136–1146, Jan. 2020, doi: 10.1109/tpel.2019.2923726.
- [100] S. K. Sahoo and T. Bhattacharya, "Field weakening strategy for a vector-controlled induction motor drive near the six-step mode of operation," *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 3043–3051, Apr. 2016, doi: 10.1109/tpel.2015.2451694.
- [101] F. Xie, W. Hong, W. Wu, K. Liang, and C. Qiu, "Current distribution method of induction motor for electric vehicle in whole speed range based on gaussian process," *IEEE Access*, vol. 7, pp. 165974–165984, 2019, doi: 10.1109/access.2019.2953293.
- [102] M. M. Rostami, "Analysis of indirect rotor field oriented vector control for squirrel cage induction motor drives," in *2012 IEEE International Power Engineering and Optimization Conference*, Jun. 2012, pp. 505–508, doi: 10.1109/peoco.2012.6230918.
- [103] Panchal, N. Sandeep, V. S. Sheth, and Akshay A. Pandya, "Simulation and analysis of pwm inverter fed induction motor drives," *International Journal of Emerging Trends in Electrical and Electronics (IJETEE)*, vol. 2, no. 4, pp. 18–24, 2013.
- [104] S. B. Kulkarni and R. H. Chile, "MATLAB/SIMULINK simulation tool for power systems," *International Journal of Power System Operation and Energy Management*, pp. 140–145, Oct. 2011, doi: 10.47893/ijpsoem.2011.1025.
- [105] Gajare, M. Atul, and N. R. Bhasme, "A review on speed control techniques of single-phase induction motor," *International Journal of Computer Technology and Electronics Engineering*, vol. 2, no. 5, pp. 33–39, 2012.
- [106] M. Mohapatra and B. C. Babu, "Fixed and sinusoidal-band hysteresis current controller for PWM voltage source inverter with LC filter," in *2010 IEEE Students Technology Symposium (TechSym)*, Apr. 2010, pp. 88–93, doi: 10.1109/techsym.2010.5469205.

**BIOGRAPHIES OF AUTHORS**

**Omran Alabedalkham**    is received his B.Sc. and M.Sc. degrees both in electrical engineering from Damascus University, Syria, in 2007 and 2011 respectively. and a Ph.D. degree from Dicle University, Türkiye, in 2023. He is currently reseacher in Research and Development Center of EFG Electrical Energy Company, Türkiye. His research interests include electric machinery, control of electric machine, power electronics, renewable energy. He can be contacted at email: omran.khamis@gmail.com.



**Baran Karahan**    received his B.Sc. degrees electrical engineering from Gaziantep University, Türkiye, in 2023. He is currently reseacher in Research and Development Center of EFG Electrical Energy Company, Türkiye. His research interests include high-voltage switching devices, renewable energy. He can be contacted at email: brnkrhn27@gmail.com.



**İbrahim İdiz**    received his B.Sc. degree in Electrical and Electronics Engineering from Siirt University in 2018. He is currently working as a researcher at the Research and Development Center of EFG Electrical Energy Company, Türkiye. His research interests include medium- and high-voltage switchgear and power systems, electrical insulation and isolation technologies, epoxy- and composite-based materials, dielectric behavior analysis, and advanced engineering applications for smart energy systems. He can be contacted at email: ibrahimidiz.eem@gmail.com.



**Hüseyin Alptekin**    received his B.Sc. and M.Sc. degrees both in electrical engineering from from Harran University, Türkiye, in 2019 and 2022 respectively. He is currently reseacher in Research and Development Center of EFG Electrical Energy Company, Türkiye. His research interests include electric machinery, control of electric machine, composite and hybrid materials, mechanical, Nanotechnology and renewable energy. He can be contacted at email: hsynalptkn21@gmail.com.



**Enver Ediz Erol**    received his B.Sc. degree from Süleyman Demirel University in 2016. He is currently a M.Sc. student at Dicle University. In parallel, he is actively working as a researcher at the Research and Development Center of EFG Electrical Energy Company. His research interests focus on high-voltage switching devices, electrical machines. He can be contacted at email: enverediz.erol@efgelektrik.com.