



Regenerative Braking of an Induction Motor Drive: Comparative Evaluation of V/f and Field-Oriented Control Using a d-q Dynamic Model

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ABSTRACT

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regenerative braking, induction-motor drive, V/f control, field-oriented control, d-q dynamic model, electric vehicles

Regenerative braking in electric vehicles (EVs) depends strongly on the transient response of the traction-motor control system. This study compares scalar volt-per-hertz (V/f) control and field-oriented control (FOC) for regenerative braking in an induction-motor drive. A dynamic d-q model of the motor, inverter, and DC link was derived from the governing equations and implemented in MATLAB/Simulink without specialized machine-model libraries. The model was validated against bench measurements and evaluated over the FTP72 and SC03 driving cycles. An equivalent Simscape implementation was used as a benchmark for numerical accuracy and simulation execution time. Under the reported test conditions, FOC delivered a higher regenerative-energy recovery rate than V/f control, reaching 4.047% and 2.212%, respectively. For the 195 s SC03 cycle with a fixed 10 μ s time step, the V/f model completed the simulation in 1320 s, compared with 1620 s for the FOC model. The results indicate a trade-off between regenerative-energy recovery and computational demand: FOC provides stronger braking-energy recuperation, whereas V/f offers a less computationally demanding alternative. The present model represents the DC link by a DC supply and capacitor; battery dynamics and energy-management strategies are therefore outside the scope of this study.

1. INTRODUCTION

Electric vehicles (EVs) have now become a crucial solution in global efforts to reduce carbon emissions, where energy efficiency is a key determinant of their performance. Regenerative braking (RB) is widely used in modern EVs as a primary strategy to extend driving range [1]. This is achieved by transitioning the motor function into a generator during vehicle deceleration. Therefore, the RB system represents the most effective energy recovery method compared to other on-board strategies, such as solar panels, regenerative suspension, or wind turbines [2]. Despite its great potential, the efficient implementation of this system on induction motor-based powertrains presents significant technical challenges, particularly in bidirectional power flow management. However, controlling the regenerative braking system is much more complex, especially with asynchronous (induction) motors, because it demands precise inverter control to channel electrical energy from the AC motor back to the battery [2, 3]. The highly non-linear dynamics of induction motors make independent flux and torque regulation difficult without sophisticated control strategies. This difficulty arises because the inverter requires an algorithm (logic) capable of calculating precise switching signals in real-time to force the motor to generate negative torque (braking torque) [4]. This necessitates the use of control algorithms such as volt-per-hertz (V/f) and field-oriented control (FOC), as both provide the logic required to operate the motor in generator mode [5].

The selection between these two strategies often involves a trade-off between braking performance, energy efficiency, and computational complexity that has not been fully explored.

Table 1. State-of-the-art comparison of related studies

References	Model d-q	Adaptive	Regenerative Braking	FOC	V/f
Xie et al. [6]	Yes	Yes	Yes	No	Yes
Armando et al. [7]	Yes	No	Yes	Yes	No
Albarri et al. [8]	Yes	Yes	Yes	Yes	No
Shabandokht-Zarami et al. [9]	Yes	No	No	Yes	No
Kousalya and Singh [10]	Yes	No	No	Yes	No
Proposed Method	Yes	Yes	Yes	Yes	Yes

Note: FOC: field-oriented control; V/f: volt-per-hertz.

Based on Table 1 on the state-of-the-art, it is observed that although previous studies [6-8] have considered the regenerative braking aspect, and some of them [6, 8] have implemented adaptive control to respond to system dynamics, no study has comprehensively combined all these elements into a single comparative framework. The majority of studies focus on one specific control strategy, whether it is solely FOC

as in previous studies [7-10] or the V/f control approach [6]. This lack of direct (head-to-head) comparative studies creates a knowledge gap in determining the optimal control strategy for dynamic braking scenarios. This study addresses the identified gap by proposing a novel d-q mathematical model integrated with an adaptive proportional-integral (PI) controller. The proposed model demonstrates robustness against varying driving patterns while maintaining a low computational load. Furthermore, this study conducts a direct comparison between the performance of FOC and V/f control under regenerative braking scenarios, providing critical insights into the most efficient control strategy for electric vehicle applications. Furthermore, this study aims to validate the accuracy of the proposed model through comparison with hardware experiments.

The systematic writing of this paper is arranged as follows: Section 2 presents the comprehensive mathematical modeling of the EV powertrain system. Section 3 details the motor control system modeling for regeneration mode using V/f and FOC. Section 4 outlines the simulation methodology and testing scenarios. Section 5 provides an analysis of the performance comparison and energy regeneration results, followed by the study conclusion in Section 6.

2. MATHEMATICAL MODELING OF THE ELECTRIC VEHICLE POWERTRAIN SYSTEM

2.1 Vehicle dynamics and mechanical load

The mathematical model of the mechanical load and equations of motion determine how motor torque is converted into speed. In this study, the mechanical load model is simplified from complex EV dynamics into a viscous friction load model [11]. In the viscous friction model, the Load Torque is assumed to be proportional to the rotor mechanical speed, where F is the viscous friction coefficient used in Eqs. (1) and (2).

$$T_L = F \cdot \omega_{rm} \quad (1)$$

$$\omega_{rm} = \frac{\omega_r}{P/2} \quad (2)$$

Based on Newton's Second Law, this equation calculates the rotor speed as a result of the difference between the electromagnetic torque T_e generated by the motor and the load torque. The relationship between these two torques can be seen in Eq. (3).

$$T_e = J \frac{d\omega_r}{dt} + B_m \omega_r + T_L \quad (3)$$

The inertia J is converted to the electrical domain. Thus, the equation used to relate the two torques in this study is shown in Eq. (4).

$$\frac{d\omega_r}{dt} = (T_e - T_L) \cdot \left(\frac{P}{2J} \right) \quad (4)$$

2.2 Induction machine model

The analysis of this model begins by setting the reference frame speed to 0 to establish a motor model observable from

the stator side [11]. Subsequently, the three-phase stator variables are transformed into two-phase stationary variables to obtain the overall flux parameters for constructing the induction motor [12, 13]. The induction machine model is constructed by setting the reference frame to 0 so that it can be observed from the stator side using the reference frame equation in Eq. (5).

$$\omega = \frac{d\theta}{dt} \quad (5)$$

The three-phase stator variables f_{abc} are transformed into two-phase stationary variables and the zero component f_{qd0s} using the Park Transformation matrix, as shown in Eqs. (6) to (9).

$$f_{qd0s} = K_s f_{abc} \quad (6)$$

$$(f_{qd0s})^T = [f_{qs} \quad f_{ds} \quad f_{0s}] \quad (7)$$

$$(f_{abc})^T = [f_{as} \quad f_{bs} \quad f_{cs}] \quad (8)$$

The transformation matrix K_s used for the abc to d-q conversion is defined as Eq. (9) [13]. Using this matrix, the three-phase input voltages v_{as}, v_{bs}, v_{cs} are converted into stationary d-q voltage components, namely v_{qs} and v_{ds} , as shown in Eqs. (10) and (11).

$$K_s = \frac{2}{3} \cdot \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ \sin \theta & \sin \left(\theta - \frac{2\pi}{3} \right) & \sin \left(\theta + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (9)$$

$$v_{qs} = \frac{2}{3} \left(v_{as} \cos \theta + v_{bs} \cos \left(\theta - \frac{2\pi}{3} \right) + v_{cs} \cos \left(\theta + \frac{2\pi}{3} \right) \right) \quad (10)$$

$$v_{ds} = \frac{2}{3} \left(v_{as} \sin \theta + v_{bs} \sin \left(\theta - \frac{2\pi}{3} \right) + v_{cs} \sin \left(\theta + \frac{2\pi}{3} \right) \right) \quad (11)$$

The dynamic motor flux equations are then calculated based on the system base frequency ω_b in Eq. (12).

$$\omega_b = 2\pi f \quad (12)$$

Eqs. (13) and (14) are the derivative equations for the stator flux (ψ_{qs}, ψ_{ds}), whereas Eqs. (15) and (16) are the derivative equations for the rotor flux (ψ'_{qr}, ψ'_{dr}).

$$\psi_{qs} = \frac{d\omega_b}{dt} \left[v_{qs} - \frac{\omega}{\omega_b} \psi_{ds} + \frac{r_s}{X_{ls}} (\psi_{mq} - \psi_{qs}) \right] \quad (13)$$

$$\psi_{ds} = \frac{d\omega_b}{dt} \left[v_{ds} + \frac{\omega}{\omega_b} \psi_{qs} + \frac{r_s}{X_{ls}} (\psi_{md} - \psi_{ds}) \right] \quad (14)$$

$$\psi'_{qr} = \frac{d\omega_b}{dt} \left[v'_{qr} - \left(\frac{\omega - \omega_r}{\omega_b} \right) \psi'_{dr} + \frac{r'_r}{X'_{lr}} (\psi_{mq} - \psi_{qr}) \right] \quad (15)$$

$$\psi'_{dr} = \frac{d\omega_b}{dt} \left[v'_{dr} + \left(\frac{\omega - \omega_r}{\omega_b} \right) \psi'_{qr} + \frac{r'_r}{X'_{lr}} (\psi_{md} - \psi'_{dr}) \right] \quad (16)$$

The magnetization flux and equivalent reactance equations connecting the stator and rotor components are defined in Eqs. (17) to (19).

$$\psi_{mq} = X_{aq} \left(\frac{\psi_{qs}}{X_{ls}} + \frac{\psi'_{qr}}{X'_{lr}} \right) \quad (17)$$

$$\psi_{md} = X_{ad} \left(\frac{\psi_{ds}}{X_{ls}} + \frac{\psi'_{dr}}{X'_{lr}} \right) \quad (18)$$

$$X_{aq} = X_{ad} = \left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X'_{lr}} \right)^{-1} \quad (19)$$

From the flux model above, the d-q component currents for the stator (i_{qs} , i_{ds}) and rotor (i'_{qr} , i'_{dr}) can be calculated using Eqs. (20) to (23).

$$i_{qs} = \frac{1}{X_{ls}} (\psi_{qs} - \psi_{mq}) \quad (20)$$

$$i_{ds} = \frac{1}{X_{ls}} (\psi_{ds} - \psi_{md}) \quad (21)$$

$$i'_{qr} = \frac{1}{X'_{lr}} (\psi'_{qr} - \psi_{mq}) \quad (22)$$

$$i'_{dr} = \frac{1}{X'_{lr}} (\psi'_{dr} - \psi_{md}) \quad (23)$$

The main objective of this electrical modeling is to calculate the Electromagnetic Torque generated by the motor. The Electromagnetic Torque is formulated from the rotor flux and current components, as seen in Eq. (24).

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) \left(\frac{1}{\omega_b} \right) (\psi'_{qr} i'_{dr} - \psi'_{dr} i'_{qr}) \quad (24)$$

For feedback or visualization purposes, the d-q currents can be converted back to the three-phase abc domain using the inverse transformation matrix K_s^{-1} , as shown in Eqs. (25) through (28) [14, 15].

$$K_s^{-1} = \begin{bmatrix} \cos \theta & \sin \theta & 1 \\ \cos \left(\theta - \frac{2\pi}{3} \right) & \sin \left(\theta - \frac{2\pi}{3} \right) & 1 \\ \cos \left(\theta + \frac{2\pi}{3} \right) & \sin \left(\theta + \frac{2\pi}{3} \right) & 1 \end{bmatrix} \quad (25)$$

$$i_{as} = i_{qs} \cos \theta + i_{ds} \sin \theta \quad (26)$$

$$i_{bs} = i_{qs} \cos \left(\theta - \frac{2\pi}{3} \right) + i_{ds} \sin \left(\theta - \frac{2\pi}{3} \right) \quad (27)$$

$$i_{cs} = i_{qs} \cos \left(\theta + \frac{2\pi}{3} \right) + i_{ds} \sin \left(\theta + \frac{2\pi}{3} \right) \quad (28)$$

The Electromagnetic Torque obtained from Eq. (24) is the electrical output of the motor [6]. This torque is then input into the mechanical motion Eq. (4), which relates the Electromagnetic Torque to the load torque to calculate the new rotor speed [14, 15].

2.3 Three-phase inverter model

The three-phase voltage source inverter (VSI) serves as an interface between the battery (DC source) and the induction motor (AC load) [16]. In this study, the inverter is controlled using the Sine-Triangle Pulse Width Modulation (SPWM) method. Three sine wave reference signals are calculated using Eqs. (29) through (31).

$$d_a = d \cos \theta_c \quad (29)$$

$$d_b = d \cos \left(\theta_c - \frac{2\pi}{3} \right) \quad (30)$$

$$d_c = d \cos \left(\theta_c + \frac{2\pi}{3} \right) \quad (31)$$

Then, the three reference signals are compared with a single high-frequency triangular carrier wave to generate six complementary gating signals to obtain voltage values using Eqs. (32) to (34) [17].

$$v_{as} = \frac{2}{3} v_{ag} - \frac{1}{3} v_{bg} - \frac{1}{3} v_{cg} \quad (32)$$

$$v_{bs} = \frac{2}{3} v_{bg} - \frac{1}{3} v_{ag} - \frac{1}{3} v_{cg} \quad (33)$$

$$v_{cs} = \frac{2}{3} v_{cg} - \frac{1}{3} v_{ag} - \frac{1}{3} v_{bg} \quad (34)$$

And the regenerative DC returning to the source is obtained using Eqs. (35) to (38) [14, 15].

$$i_{adc} = i_{as} \cdot T_1 \quad (35)$$

$$i_{bdc} = i_{bs} \cdot T_2 \quad (36)$$

$$i_{cdc} = i_{cs} \cdot T_3 \quad (37)$$

$$i_{dc} = i_{adc} + i_{bdc} + i_{cdc} \quad (38)$$

3. MOTOR CONTROL SYSTEM MODELING FOR REGENERATION

3.1 Basic principles of regenerative braking

The basic principle of regenerative braking is to enable the induction motor to operate as a generator during deceleration [18]. An induction motor can rapidly transition between motoring and generating operations based on the concept of slip [19]. Slip is the relative speed difference between the synchronous speed of the stator magnetic field and the actual mechanical speed of the rotor [20]. The mathematical value of slip is given in Eq. (39) [14, 15].

$$s = \frac{\omega_{ms} - \omega_r}{\omega_{ms}} \quad (39)$$

The motor torque characteristics with respect to slip and speed are clearly shown in Figure 1.

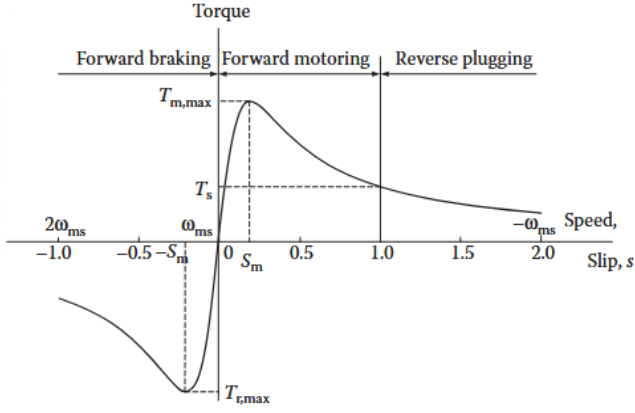


Figure 1. Induction motor torque-slip characteristic [6]

In normal operation mode, known as forward motoring, the rotor speed is always slightly below the synchronous speed [21]. This results in a positive slip value in the range of $0 < s < 1$, which creates positive torque to propel the vehicle [22]. However, regenerative braking occurs under the opposite conditions. When the rotor speed exceeds the synchronous speed, the slip value becomes negative [23]. This negative slip condition is the core of regenerative braking. When $s < 0$, the motor automatically generates negative torque [24]. This negative torque opposes the wheel rotation, creating a braking effect and causing the motor to operate as a generator, returning electrical power to the source [25]. Therefore, the primary task of the regenerative braking control system, whether V/f or FOC, is to actively manipulate the stator frequency to create a condition where the synchronous speed of the magnetic field is lower than the actual rotor speed [26].

3.2 Volt-per-hertz control modeling

In this study, the V/f control requires a smoother to generate a raw mechanical speed reference. The raw speed reference is then passed through a slew rate limiter block to create a smooth ramp (linear change) for the speed reference. During regenerative braking, this is the block that linearly decreases the reference frequency, forcing the negative slip condition described in Subsection 3.1. Its output is then converted to the electrical domain as a frequency reference. The V/f control here aims to maintain the motor flux constant [27]. To achieve this, the stator voltage magnitude v_s is calculated to be proportional to the frequency, as shown in Eq. (40). This v_s value is then used to calculate the modulation index d required for the SPWM inverter using Eq. (41) [14, 15].

$$v_s = \frac{v_{nom}}{\sqrt{3}} \sqrt{\frac{r_s^2 + \omega_e^2 L_s^2}{r_s^2 + \omega_b^2 L_s^2}} \quad (40)$$

$$d = \frac{v_s \sqrt{2}}{v_{dc}/2} \quad (41)$$

The V/f model utilized is not purely open-loop as it includes slip compensation for improved accuracy [28, 29]. After obtaining the transformed currents, the slip compensation, slip correction, and motor constants are obtained using Eqs. (42) through (44) [15].

$$i_s = \frac{1}{\sqrt{2}} \sqrt{i_{qs}^2 + i_{ds}^2} \quad (42)$$

$$\chi_{corr\ raw} = \frac{3P \left((v_s \sqrt{2}) \cdot i_{qs} - 2 \cdot r_s \cdot i_s \right)}{K_{tv}} \quad (43)$$

$$K_{tv} = \frac{3 \left(\frac{P}{2} \right) L_m^2 \cdot r'_r \cdot \frac{v_{nom}}{\sqrt{3}}}{r'^2_r (r_s^2 + \omega_b^2 \cdot L_s^2)} \quad (44)$$

The raw correction factor is then smoothed using a low-pass filter in Eq. (45), and the time constant for this filter is based on the inverter switching frequency, as shown in Eq. (46) [14, 15].

$$\chi_{corr} = \frac{1}{\tau s + 1} \cdot \chi_{corr\ raw} \quad (45)$$

$$\tau = \frac{1}{\left(2 \cdot \pi \cdot \frac{f_{switch}}{10} \right)} \quad (46)$$

The final synchronous frequency to be sent to the inverter is obtained by combining the reference frequency with the slip correction factor in Eq. (47) [14, 15].

$$\omega_e = \frac{\omega_e^* + \sqrt{\max(0, \omega_e^{*2} + \chi_{corr})}}{2} \quad (47)$$

3.3 Field-oriented control modeling

In this study, FOC also utilizes the same smoother as the V/f control. Unlike V/f, FOC employs a sophisticated closed-loop control architecture. This Proportional–Integral–Derivative (PID) controller compares the speed reference with the actual rotor speed to generate the electromagnetic torque reference in Eqs. (48) through (52) [14, 15].

$$T_e^* = \left(-\frac{\omega_r}{\frac{P}{2}} K_{sc} \right) + \omega_e^* + \int \left(\left(\omega_e^* - \frac{\omega_r}{\frac{P}{2}} \right) \cdot \left(\frac{1}{T_{sc}} \right) + (T_e^* - T_{e\ raw}^*) \right) + -\frac{\omega_r \cdot (K_d \cdot N_{filter} \cdot s)}{\frac{P}{2} (s + N_{filter})} \quad (48)$$

$$T_{e\ max} = -T_{e\ min} = \left(\frac{P_{nom}}{speed_{rated} \cdot \frac{2\pi}{60}} \right) \cdot 110\% \quad (49)$$

$$i_{ds}^* = \frac{\lambda'_{dr}}{L_M} \quad (50)$$

$$i_{qs}^* = \frac{T_e^* \cdot 4 \cdot L'_r}{\lambda'_{dr} \cdot 3 \cdot P \cdot L_M} \quad (51)$$

$$\omega_e = \omega_r + \frac{r'_r}{L'_r} \cdot \frac{i_{qs}^*}{i_{ds}^*} \quad (52)$$

FOC operates within a synchronously rotating d–q reference frame [30]. Feedback currents must be transformed from the stationary frame to the synchronous frame using the transformation matrix K^{xy} in Eqs. (53) and (54).

$$f_{qd0s}^y = K^{xy} f_{qd0s}^x \quad (53)$$

$$K^{xy} = \begin{bmatrix} \cos(\theta_y - \theta_x) & -\sin(\theta_y - \theta_x) & 0 \\ \sin(\theta_y - \theta_x) & \cos(\theta_y - \theta_x) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (54)$$

These measured currents are then fed into the internal current control loop. This loop employs two independent anti-windup PI controllers, one for the q-axis (torque) and one for the d-axis (flux). These PI controllers calculate the raw reference voltage required to force the measured current to match the reference current. Eqs. (55) and (56) define the anti-windup PI logic used [14, 15].

$$v_{qs\ raw} = (i_{qs}^* - i_{qs\ meas}) \cdot K_p + \int \left((i_{qs}^* - i_{qs\ meas}) \cdot \frac{K_p}{T_i} + (v_{qs} - v_{qs\ raw}) \right) \quad (55)$$

$$v_{ds\ raw} = (i_{ds}^* - i_{ds\ meas}) \cdot K_p + \int \left((i_{ds}^* - i_{ds\ meas}) \cdot \frac{K_p}{T_i} + (v_{ds} - v_{ds\ raw}) \right) \quad (56)$$

In the saturation section, there is also a limitation applied using Eq. (57) [15].

$$v_{max} = -v_{min} = \frac{v_{nom} \cdot \sqrt{2}}{\sqrt{3}} \quad (57)$$

Eqs. (58) and (59) are used to calculate the final reference voltage by adding compensation [15].

$$v_{qs}^* = v_{qs\ raw} + i_{ds}^* \cdot (\omega_e \cdot L_s) \quad (58)$$

$$v_{ds}^* = v_{ds\ raw} - i_{qs}^* \cdot (\omega_e \cdot L_s) \quad (59)$$

Then, the values v_{qs}^* and v_{ds}^* are transformed back to the stationary reference frame using Eq. (60) [15].

$$K^{(xy)-1} = K^{(xy)T} \quad (60)$$

Scaling calculations are performed to obtain d_a, d_b, d_c using Eqs. (61) through (63) [15].

$$d_a = \frac{2 \cdot v_{as}}{v_{dc}} \quad (61)$$

$$d_b = \frac{2 \cdot v_{bs}}{v_{dc}} \quad (62)$$

$$d_c = \frac{2 \cdot v_{cs}}{v_{dc}} \quad (63)$$

4. SIMULATION METHODOLOGY AND SCENARIO

4.1 Integrated powertrain simulation model design

The system topology for the powertrain is presented in Figure 2. It consists of a DC battery, a three-phase VSI utilizing switches T1-T6 and diodes D1-D6 connected to an induction motor. A control unit implements V/f or FOC to

operate the inverter and manage the motor.

To analyze and compare the regenerative braking performance of both control strategies, a complete EV powertrain system model was built using MATLAB/Simulink. This study implements two separate simulation architectures, as shown in Figure 3 for the V/f control system and Figure 4 for the FOC control system [31].

To serve as a benchmark in evaluating the performance of the proposed manual control of all components, the study compares it with V/f and FOC control utilizing full built-in Simscape blocks that are commonly used, with the configuration shown in Figure 5.

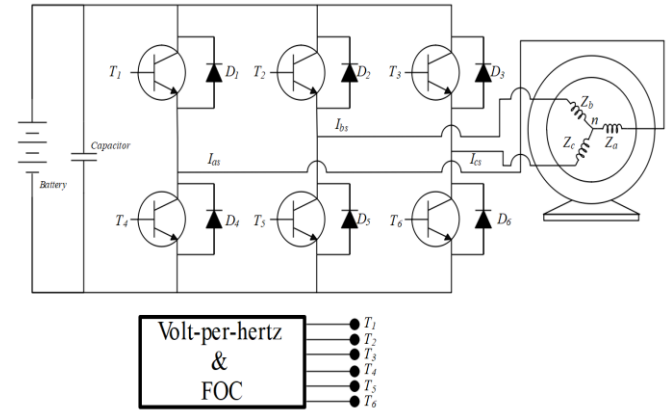


Figure 2. Electric vehicle (EV) system topology

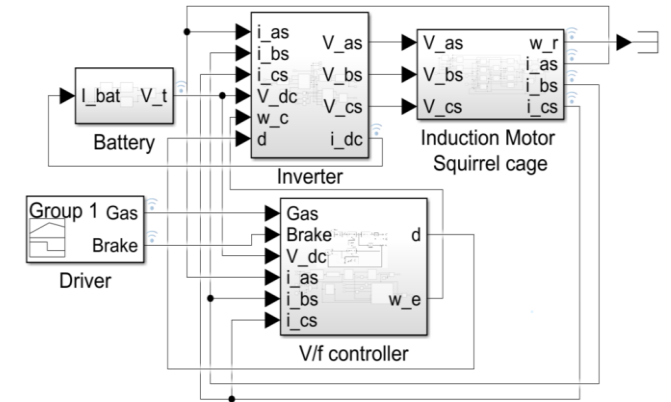


Figure 3. Electric vehicle (EV) powertrain system simulation diagram with volt-per-hertz (V/f) control

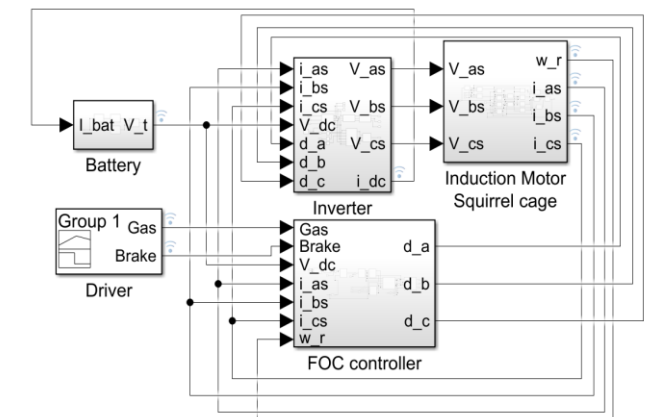


Figure 4. Electric vehicle (EV) powertrain system simulation diagram with field-oriented control (FOC)

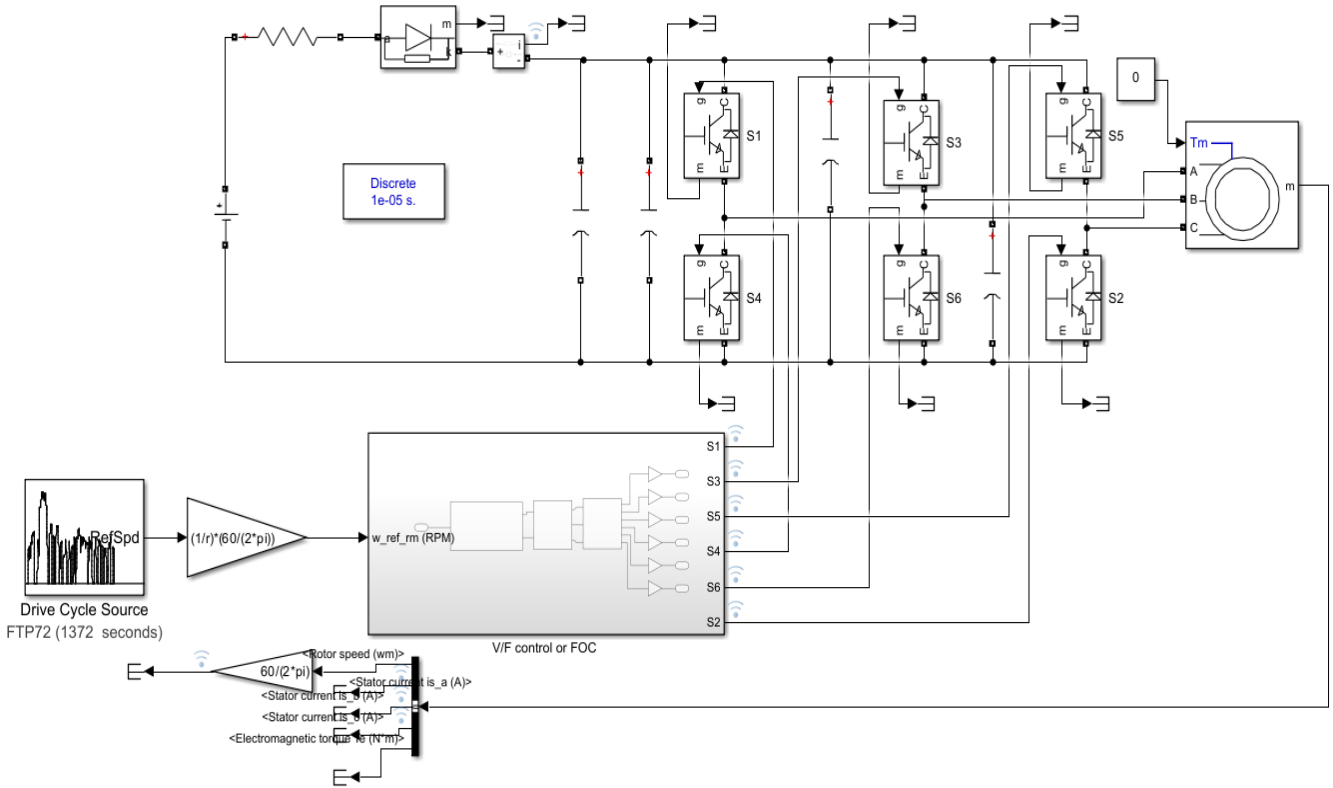


Figure 5. Electric vehicles (EVs) powertrain system simulation diagram MATLAB/Simulink

Table 2. Squirrel cage induction motor parameters

Parameter	Specification
Rated power	186 W
Rated speed	1425 RPM
Rated line voltage	190 V
Rated Frequency	50 Hz
Pole pairs	2
Stator resistance	9.9 Ω
Rotor resistance	8.15 Ω
Stator inductance	278.6 mH
Rotor inductance	285.3 mH
Mutual inductance	265.1 mH
Moment of inertia	0.001118 kgm ²
Viscous friction	0.0006076
Rated flux	0.493 Wb
Rated torque	1.25 Nm



Figure 6. Actual hardware test

4.2 Simulation parameters

In conducting the simulation, the study utilized parameters

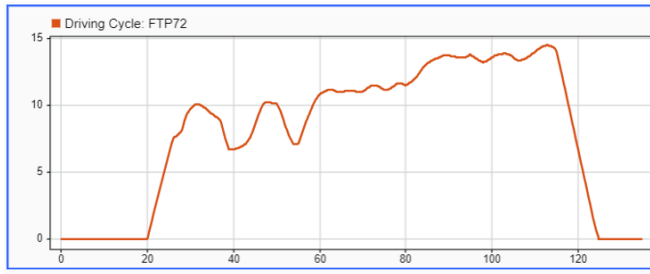
from actual components that will also be tested in the hardware setup to demonstrate that this comparison model corresponds to the real hardware. The main parameters for the squirrel cage induction motor are listed in Table 2.

This test employs a 120 V DC supply and a 0.0047 F DC-link capacitor to observe the negative current resulting from regenerative braking. This test maintains the switching frequency at 5 kHz for both controls. The hardware test setup can be seen in Figure 6.

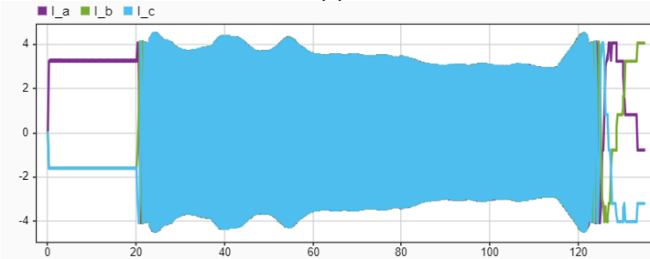
5. RESULTS AND COMPARATIVE ANALYSIS

5.1 Analysis of torque, DC voltage, current DC, current phase, and rotor speed response

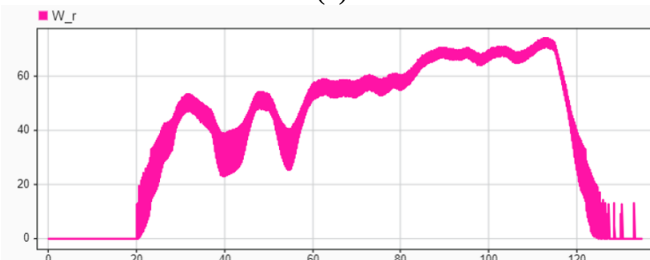
The simulation model designed using the basic equations from Section 2 and Section 3 was tested by observing the torque, DC voltage, DC, three-phase currents of the induction motor, and its rotor speed. All of these were tested under two standard driving cycles: FTP72 and SC03. This test will also provide information regarding the effect of V/f and FOC in controlling power flow during traction and motoring modes. As seen in Figures 7-10, although only using manual V/f and FOC controls based on equations, the d-q mathematical model can demonstrate how the phase current conditions synchronize with the reference speed actions in m/s. The phase current from the V/f control exhibits a sinusoidal waveform ranging from -4.5 A to 4.5 A under both driving cycle conditions, as shown in Figures 7(b) and 9(b). Meanwhile, the phase current from the FOC control achieves a reduction in current usage to a range of -2.6 A to 2.6 A, despite using the exact same induction motor, as seen in Figures 8(b) and 10(b).



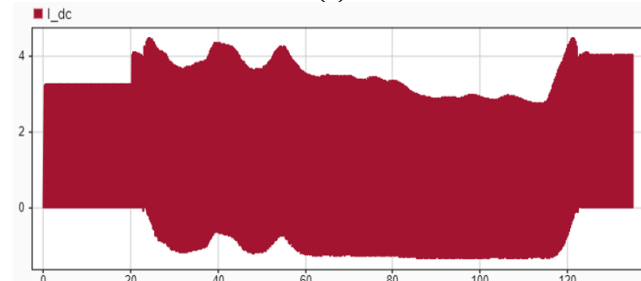
(a)



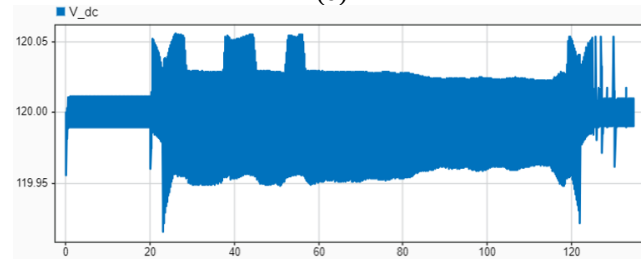
(b)



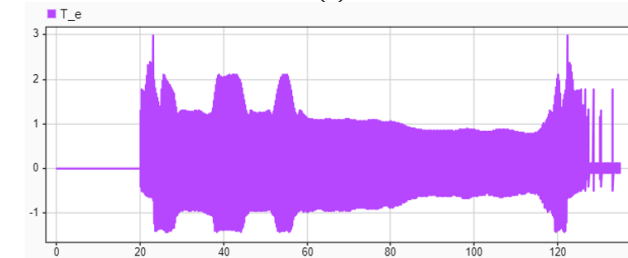
(c)



(d)

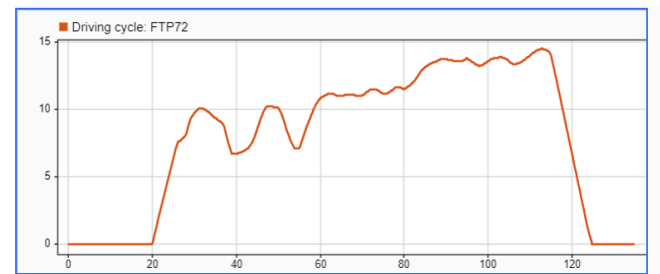


(e)

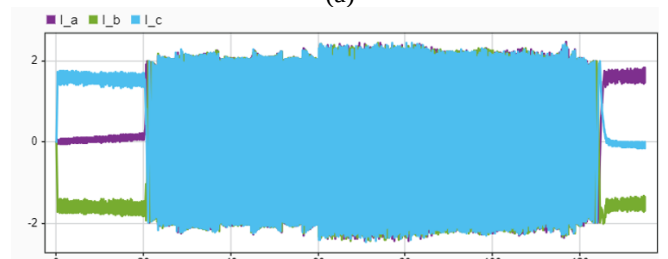


(f)

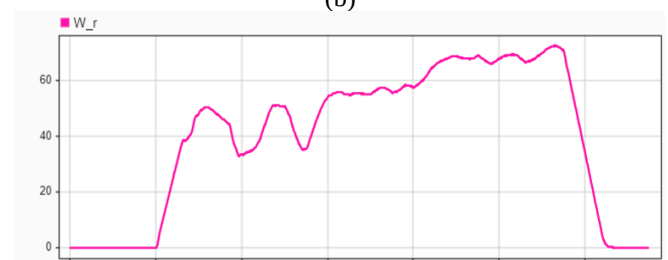
Figure 7. Test results of the proposed electric vehicle (EV) powertrain with volt-per-hertz (V/f) control in the FTP72 driving cycle: (a) driving cycle graph; (b) induction motor phase current; (c) rotor speed; (d) DC; (e) DC voltage; (f) electromagnetic torque



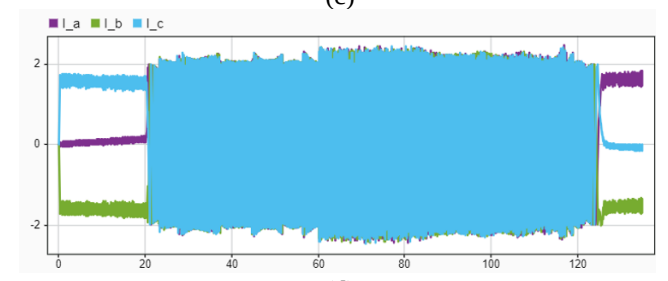
(a)



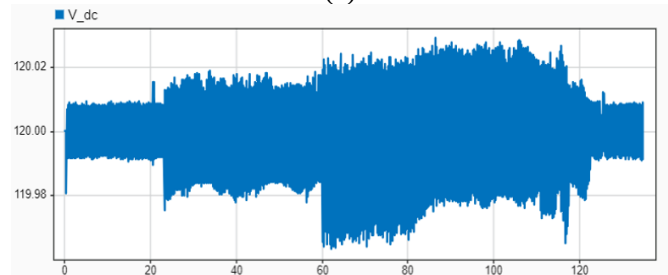
(b)



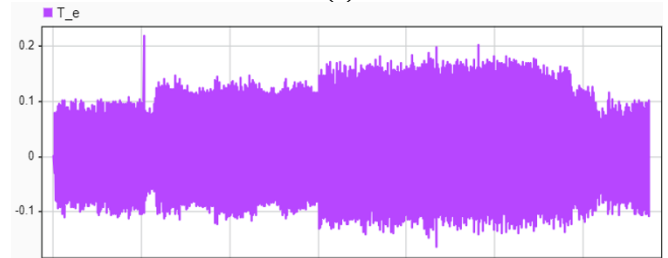
(c)



(d)

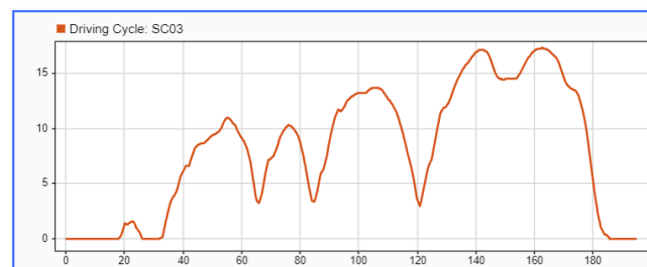


(e)

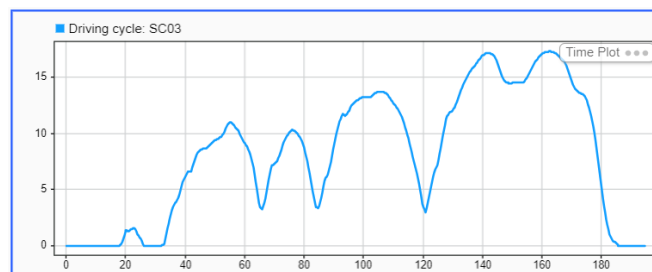


(f)

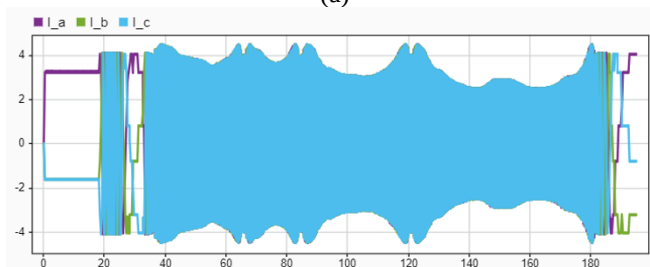
Figure 8. Test results of the proposed electric vehicle (EV) powertrain with field-oriented control (FOC) in the FTP72 driving cycle: (a) driving cycle graph; (b) induction motor phase current; (c) rotor speed; (d) DC; (e) DC voltage; (f) electromagnetic torque



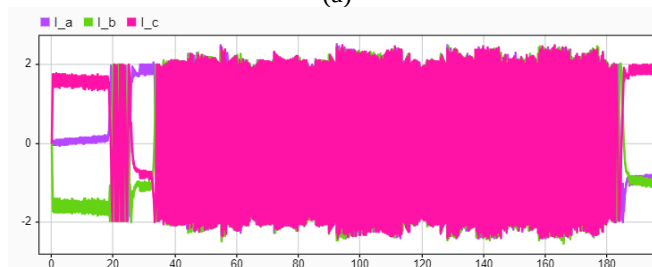
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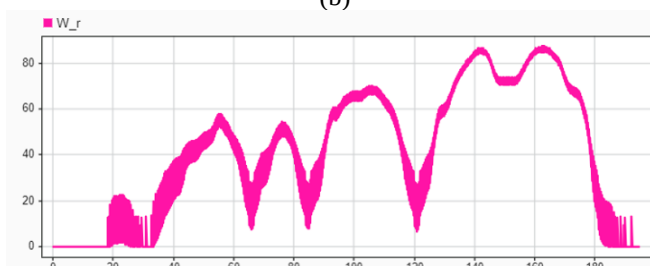
(a)



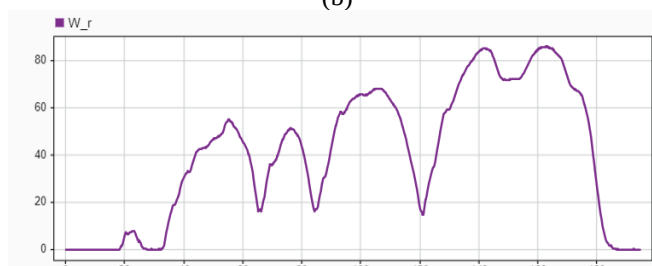
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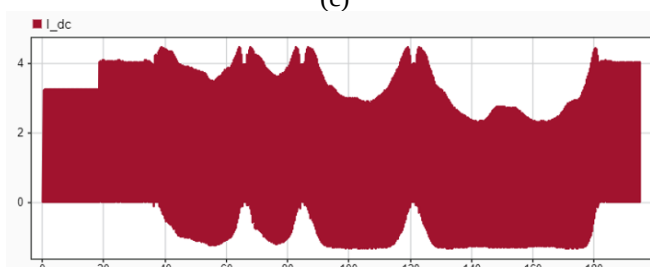
(b)



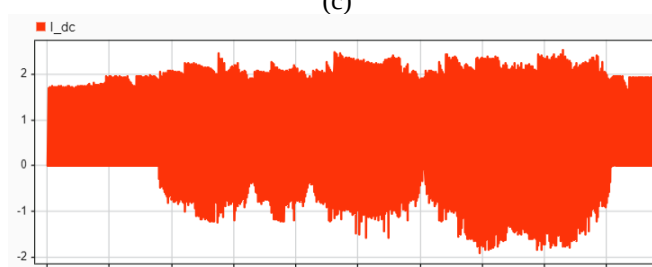
(c)



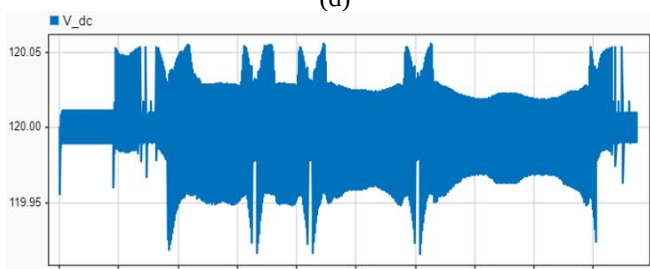
(c)



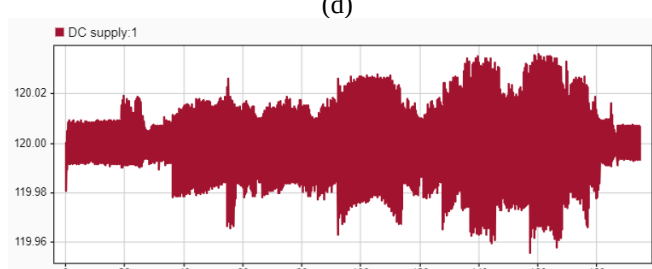
(d)



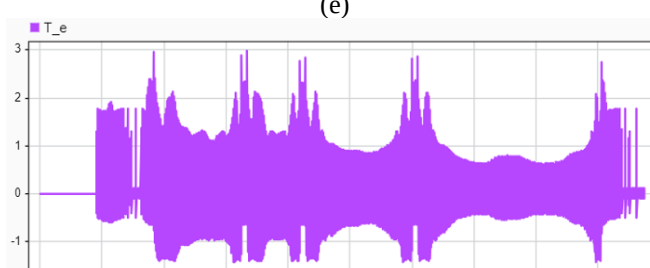
(d)



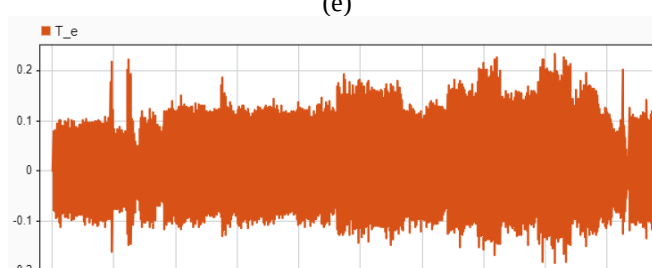
(e)



(e)



(f)



(f)

Figure 9. Test results of the proposed electric vehicle (EV) powertrain with volt-per-hertz (V/f) control in the SC03 driving cycle: (a) driving cycle graph; (b) induction motor phase current; (c) rotor speed; (d) DC; (e) DC voltage; (f) electromagnetic torque

Figure 10. Test results of the proposed electric vehicle (EV) powertrain with field-oriented control (FOC) in the SC03 driving cycle: (a) driving cycle graph; (b) induction motor phase current; (c) rotor speed; (d) DC; (e) DC voltage; (f) electromagnetic torque

Table 3. Detailed performance comparison of both controls

Parameter	Volt-Per-Hertz (V/f) Control		Field-Oriented Control (FOC)	
	FTP72 (135 s)	SC03 (195 s)	FTP72 (135 s)	SC03 (195 s)
Maximum Phase Current (A)	4.51	4.54	2.62	2.65
Maximum Electromagnetic Torque (Nm)	2.99	3	0.23	0.24
Rotor Speed Tracking Accuracy (%)	84.3	99.7	89.6	99.8
Maximum DC Current (Motoring) (A)	4.29	4.31	2.39	2.51
Minimum DC Current (Regenerating) (A)	-1.14	-1.32	-1.28	-1.93

In terms of electromagnetic torque, both control strategies successfully track the reference speed. However, the electric torque generated by the V/f control peaks at 3 Nm. This magnitude is 2.4 times greater than the rated motor torque of 1.25 Nm, potentially leading to thermal overloading of the motor under prolonged operation. However, as seen in Figures 7(f) and 9(f), this torque peak is only active at the start of speed increase to merely overcome inertia. After the acceleration transition, the motor's electric torque decreases to 0.92 Nm. In contrast to the model using FOC control, the electric torque has a maximum torque of only 0.23 Nm, which is well below the rated torque from the motor specifications. However, it can be observed in both driving cycles that although there is no reference speed yet, the electric torque from the FOC control is already active, unlike the V/f control, which remains constant at 0 Nm. This is because FOC operates in a closed loop, where it injects phase current first to generate magnetic flux before the motor moves, creating a standby mode before motor movement. The appearance of this initial phase current can be seen from 0 to 20 s in Figures 8(b) and 10(b). This differs from the open-loop V/f control, where at a 0 m/s speed reference, the inverter maintains the phase current at 0, as seen from 0 to 20 s in Figures 7(b) and 9(b).

The effect of the electric torque characteristics in both controls is clearly visible in the induction motor rotor speed in Figures 7(c), 8(c), 9(c), and 10(c). In Figures 7(c) and 9(c), the rotor speed of the induction motor for V/f control follows its reference speed. However, the accuracy of this rotor speed tracking is only 84.3% relative to the reference speed because it relies solely on the SPWM signal to mimic the reference speed and does not consider the current rotor speed. However, this rotor speed tracking could actually be improved with the driving cycle if the switching frequency were increased. In contrast to FOC, as seen in Figures 8(c) and 10(c), the rotor

speed can follow the reference speed with an accuracy of up to 99.7% using the same switching frequency as the V/f control. This is because the FOC control utilizes PI controllers to determine the d-q axis values and speed for precision. Regarding the DC voltage graphs in Figures 7(e), 8(e), 9(e), and 10(e), both controls actually share similarities where the DC voltage operates around 120 V, although there are very slight voltage fluctuations because the study used a DC supply. However, it is different for the DC graphs seen in Figures 7(d), 8(d), 9(d), and 10(d), where there are differences in the maximum and minimum current values between the two controls. In V/f control, the maximum DC can reach 4.29 A, and the minimum DC can reach -1.1 A. This is because V/f control does not consider the DC, as it maintains the voltage-to-frequency ratio constant. Unlike FOC, which has a maximum current of 2.39 A and a minimum current of -1.28 A. This is because FOC considers the magnetizing current and torque current to remain at 90 degrees, allowing the current value to be optimized while still aligning with the reference speed. This minimum current value will affect the performance in regenerating energy during the regenerative braking phase. A detailed performance comparison of these two controls can be seen in Table 3.

5.2 Analysis of regeneration energy

This study also calculates energy consumption, energy regeneration, and the percentage of energy that can be regenerated from the total consumption using Eqs. (64) through (67) [6].

$$P(t) = V_{dc}(t) \times I_{dc}(t) \quad (64)$$

$$\text{Consumption energy} = \int_0^t P_{\text{motoring}} dt \quad (65)$$

$$\text{Regeneration energy} = \int_0^t |P_{\text{regen}}| dt \quad (66)$$

$$\text{Regeneration}(\%) = \frac{\text{Regeneration energy}}{\text{Consumption energy}} \times 100\% \quad (67)$$

The performance testing of these two controls remains based on the same two driving cycles as in Subsection 5.1. The testing with the FTP72 driving cycle was conducted for 2.25 minutes, and the SC03 driving cycle was conducted for 3.25 minutes, with a simulation time step of 10 μ s for both driving cycles. The energy calculation results from these two induction motor controls can be seen in Table 4.

Based on these two controls, regarding regenerative braking, FOC is actually superior compared to V/f control due to the consideration of magnetizing current and torque current in the form of d- and q-axes. This energy regeneration percentage will also actually continue to increase based on the duration of the driving cycle performed by the driver.

Table 4. Comparison of energy calculation results

Parameter	Volt-Per-Hertz (V/f) Control		Field-Oriented Control (FOC)	
	FTP72 (135 s)	SC03 (195 s)	FTP72 (135 s)	SC03 (195 s)
Consumption energy (Wh)	6.839	10.01	1.992	2.907
Regeneration energy (Wh)	0.1547	0.2214	0.05988	0.1177
Regen (%)	2.262	2.212	3.006	4.047

5.3 Analysis of performance model comparison of volt-per-hertz and field-oriented control

In addition to evaluating the performance of the proposed mathematical simulation model, the study also verified its conformity with experimental testing using actual hardware. The testing was conducted using identical components to those in the simulations shown in Figures 2 and 5, resulting in the circuit configuration visible in Figure 6. From the experimental testing, this study developed that the proposed simulation using the mathematical model achieved an accuracy of up to 97.3% relative to the hardware testing, slightly lower than the full MATLAB Simscape block, which achieved 99.8%. However, this value is still considered sufficient because if the actual hardware phase current is 3 A,

the proposed simulated phase current value is 2.96 A. Although the accuracy of the full Simscape simulation is quite high, the data processing load when using the Simscape block can take up to 36 minutes, which is significantly longer compared to the proposed simulation that requires only 22 minutes just for v/f control. Not only is the data processing load reduced when using the proposed comparative simulation, but this simulation also provides access to every block, as the blocks used are basic blocks combined using the physics equations explained in Section 2 and Section 3. Thus, this facilitates a more advanced analysis of the control behavior and the constituent components of the EV powertrain. The comparison of the two simulations against the hardware can be seen in Table 5.

Table 5. Comparison of simulation results with actual hardware measurements

Parameter	Volt-Per-Hertz (V/f) Control		Field-Oriented Control (FOC)	
	Full Simscape Model	Proposed Method	Full Simscape Model	Proposed Method
Execution time (s)	2160	1320	2280	1620
Accuracy relative to actual hardware (%)	99.8	96.2	98.4	97.3
Access to internal blocks	No	Yes	No	Yes

6. CONCLUSIONS

This study focuses on comparing V/f and FOC control on induction motors using the d-q mathematical method. This calculation focuses not only on these two controls but also on the entire EV powertrain components to facilitate a deep understanding of the constituent parameters of the EV powertrain. This is also undertaken because it is currently quite difficult to deeply understand the EV powertrain in order to comprehend regenerative braking. Therefore, the study developed an EV model in the form of a simulation that is accurate and has a low computational load compared to the Simscape simulation blocks commonly used in electrical simulations. With the establishment of this model, this study succeeded in testing two induction motor controls frequently used in EVs featuring regenerative braking. The study obtained important insight that the better the reference speed tracking, the higher the regenerative braking. This enhanced tracking capability is achieved by precisely regulating the magnetizing current, torque current, and actual rotor speed. Therefore, FOC becomes the superior control compared to V/f in enhancing regenerative braking. However, the simplicity of V/f control, which simply maintains the voltage and frequency relationship, serves as a good solution for maintaining a low computational load. The limitation of this study lies in the testing conducted on a 120 V DC supply, whereas it should ideally utilize a battery, and it also occasionally requires saturation to limit the frequency to only 19.1 Hz because the motor used has a rated voltage of 190 V. Therefore, the future work of this study involves considering the use of a battery that corresponds to the rated speed or is capable of operating at 50 Hz. This is beneficial so that in the future, simulations with hardware testing can be created that are more aligned with actual EV scenarios.

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NOMENCLATURE

T_L	Load torque	v_{as}, v_{bs}, v_{cs}	Three-phase input voltage
ω_{rm}	Rotor mechanical speed	v_{qs}, v_{ds}	d-q voltage
F	Viscous friction coefficient	ω_b	System base frequency
ω_r	Rotor electrical speed	f	Motor frequency (or Stator frequency)
T_e	Electromagnetic torque	ψ_{qs}, ψ_{ds}	Stator flux
B_m	Internal motor friction	ψ'_{qr}, ψ'_{dr}	Rotor flux (referred)
J	Inertia	i_{qs}, i_{ds}	Stator d-q current
ω	Reference frame speed	i'_{qr}, i'_{dr}	Rotor d-q current (referred)
f_{abcs}	Stator three-phase variables	d_a, d_b, d_c	Sinusoidal reference signal (or Sine wave reference)
f_{qd0s}	Stator d-q variables	d	Duty cycle
K_s	Transformation matrix	θ_c	Control angle (or Reference phase angle)
		v_{dc}	DC-link voltage
		I_{bat}	Battery current
		v_{OCV}	Open Circuit Voltage (OCV)
		R_{int}	Battery internal resistance
		ω_{sl}	Slip speed
		s	slip
		χ_{corr}	Slip correction factor