# SENSORLESS INDUCTION MOTOR SPEED CONTROL FOR ELECTRIC VEHICLES USING ENHANCED HYBRID FLUX ESTIMATOR WITH ANN-IFOC CONTROLLER

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To my beloved family;

my mother, Rosiah Binti Mamat; my late father, Sepeeh Bin Dollah; and my siblings:

thank you for your support and enthusiasm.

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# ABSTRACT

Basically, a speed sensor is used to sense an electric vehicle's motor speed at the rated value in order to achieve a high tracking accuracy of the speed, but the use of a sensor is costly and it is sensitive to vibrations. Therefore, this project proposed a new mechanism in order to eliminate the speed sensor by adopting an enhanced hybrid flux estimation. The voltage signal was modified using the rotor-flux-oriented current model's output for the internal stator flux controller to minimise the back-EMF error to represent a sensorless control. Artificial neural network (ANN)-field-oriented control (FOC) was used in the hybrid flux system. The function of the ANN was to improve speed-tracking performance, and the learning rate of the ANN inside the indirect FOC's structure trained using the Levenberg-Marquardt (LM) algorithm was varied in order to increase speed-tracking accuracy when combined with the improved ANN speed controller. The hyperparameters of ANNs, such as weights and biases, were randomly initialised and updated using the backpropagation (BP) algorithm in order to increase the convolution of the ANNs. The sensorless ANN-IFOC was modelled, simulated, and tested using MATLAB/Simulink for a 20Hp EV motor based on a small Renault Twizy EV model and triggered by the space-vector pulse-width modulation (SVPWM). The results of the ANN-IFOC hybrid estimator were obtained in four cases, which were 1) constant high and low speeds, 2) constant speed against parameter variation, 3) variable speed, and 4) variable load torque disturbances. All results showed that the proposed method gave excellent agreement, as compared with ANN- and PI-based conventional voltage model estimators, with increased tracking accuracy (1500 *rpm*: 99.23% and 99.60% to 99.85%; 1000 *rpm*: 98.90% and 99.45% to 99.85%; and 500 *rpm*: 97.92% and 99.10% to 99.85%). The proposed model with the sensorless speed controller showed consistent tracking accuracy with faster speed responses and gave the shortest settling time and fewer overshoots compared with the existing PI controller. Furthermore, the drive system was able to control and improve the transient response of the EV motor.

# ABSTRAK

Pada dasarnya, sensor kelajuan digunakan untuk mengesan kelajuan motor kenderaan elektrik pada nilai kadar untuk mencapai ketepatan penjejakan yang tinggi, tetapi mahal dan sensitif kepada getaran. Oleh itu, dalam projek ini, satu insentif baru untuk menghilangkan sensor kelajuan dengan menerapkan penganggar fluks hybrid. Ianya mengubahkan isyarat voltan dengan menggunakan keluaran model arus yang berorientasikan fluks pemutar untuk pengawal fluks pemegun dalaman untuk meminimumkan ralat EMF sebagai kawalan kelajuan tanpa sensor. Sistem hibrid ini telah disertakan kawalan berorientasikan medan (FOC) berdasarkan rangkaian neural buatan (ANN). Penggunaan kercerdasan ANN adalah untuk menambah baik prestasi kelajuan dengan mengubah nilai kadar pembelajaran ANN dalam struktur FOC yang tidak langsung serta telah dilatih menggunakan algoritma Levenberg-Marquardt (LM) untuk meningkatkan ketepatan penjejakan kelajuan yang mana telah dihubungkan dengan pengawal kelajuan ANN yang ditingkatkan. Hiperparameter ANN seperti berat dan bias diinisialisasi secara rawak dan dikemas kini menggunakan algoritma *backpropagation* (BP) untuk meningkatkan pelingkaran ANN. ANN-IFOC dengan struktur tanpa sensor telah dimodelkan, disimulasi dan diuji melalui MATLAB/Simulink untuk ukuran EV yang berkuasa 20 Hp berdasarkan model EV kecil Renault Twizy, serta dicetuskan oleh 5 kHz penyongsang berdasarkan *space-vector pulse-width modulation* (SVPWM). Hasil penganggar hibrid ANN-IFOC diperoleh berdasarkan empat kes seperti; 1) berkelajuan tinggi dan rendah secara berterusan, 2) kelajuan berterusan terhadap variasi parameter motor, 3) kelajuan berubah, dan 4) gangguan beban tork berubah. Pada kesemua hasil akhir, ia menunjukkan bahawa pengawal yang dicadangkan memberikan kesepakatan yang sangat baik dibandingkan dengan ANN dan PI yang berdasarkan penganggar model voltan dengan ketetapan penjejakan kelajuan meningkat dari: 1500 *rpm*: 99.23% dan 99.60% kepada 99.85%, 1000 *rpm*: 98.90% dan 99.45% kepada 99.85%, dan 500 *rpm*: 97.92% dan 99.10% kepada 99.85%. Pengawal yang dicadangkan dengan model

kelajuan tanpa sensor menunjukkan ketepatan penjejakan yang konsisten dengan tindak balas kelajuan yang lebih cepat yang memberikan masa pengenapan terpendek dan kurang terlajak berbanding pengawal PI. Tambahan pula, sistem pemacu dapat mengawal dan meningkatkan tindak balas fana motor EV.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| $V_{dq}^{s}$, $V_{dq}^{r}$ | – | Direct and quadrature of stator and rotor voltages refer to stator and rotor windings |
| $V_{dqs}^{s}$, $V_{dqr}^{s}$ | – | Direct and quadrature of stator and rotor voltages in stationary frame |
| $V_{dqs}^{e}$, $V_{dqr}^{e}$ | – | Direct and quadrature of stator and rotor voltages in synchronously rotating frame |
| $V_{DC}$ | – | DC voltage source |
| $i_{dq}^{s}$, $i_{dq}^{r}$ | – | Direct and quadrature of stator and rotor currents referring to stator and rotor windings |
| $i_{dqs}^{s}$, $i_{dqr}^{s}$ | – | Direct and quadrature of stator and rotor currents in stationary frame |
| $i_{dqs}^{e}$, $i_{dqr}^{e}$ | – | Direct and quadrature of stator and rotor currents in synchronously rotating frame |
| $V_{abc}$, $i_{abc}$ | – | Three-phase voltage and current |
| $\psi_{dq}^{s}$, $\psi_{dq}^{r}$ | – | Direct and quadrature of stator and rotor flux referring to stator and rotor windings |
| $\psi_{dqs}^{s}$, $\psi_{dqr}^{s}$ | – | Direct and quadrature of stator and rotor flux in stationary frame |
| $\psi_{dqs}^{e}$, $\psi_{dqr}^{e}$ | – | Direct and quadrature of stator and rotor flux in synchronously rotating frame |
| $\omega_r^{*}$, $\omega_e$, $\omega_r$, $\omega_{r\_est}$ | – | Reference, synchronous, measured, and estimated rotor speeds |
| $L_s$, $L_r$, $L_m$, $L_{ls}$, $L_{lr}$ | – | Stator, rotor, magnetising, stator leakage, and rotor leakage inductances |
| $R_s$, $R_r$ | – | Stator and rotor resistances |
| $\tau_e$, $\tau_l$ | – | Electromagnetic and load torques |
| $k_p$, $k_i$ | – | Proportional and integral gains |

| | | |
|---|---|---|
| $\varepsilon_{error}$ | – | Back-EMF error |
| $\gamma$ | – | Learning rate |
| $\theta_e$ | – | Rotor flux position angle |
| $J$ | – | Moment inertia |
| $\sigma$ | – | Leakage coefficient |
| $s$ | – | Slip |
| $p$ | – | Number of poles |
| $t$ | – | Time |
| EV | – | Electric vehicle |
| LCV | – | Light commercial vehicle |
| DC | – | Direct current |
| AC | – | Alternating current |
| IM | – | Induction motor |
| PWM | – | Pulse-width modulation |
| SVPWM | – | Space-vector pulse-width modulation |
| VSI | – | Voltage source inverter |
| IGBT | – | Insulated-gate bipolar transistor |
| FOC | – | Field-oriented control |
| IFOC | – | Indirect field-oriented control |
| DFOC | – | Direct field-oriented control |
| DTC | – | Direct torque control |
| VFDs | – | Variable frequency drives |
| PI | – | Proportional-integral |
| LC | – | Inductive-capacitive low pass filter |
| MRAS | – | Model reference adaptive system |
| FLC | – | Fuzzy logic control |
| SMO | – | Sliding mode observer |
| EKF | – | Extended Kalman filter |
| UKF | – | Unscented Kalman filter |
| ANNs | – | Artificial neural networks |
| MTPA | – | Maximum torque per ampere |
| VVVF | – | Variable voltage-variable frequency |
| PLL | – | Phase-locked loop |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

This chapter presents the introduction of the research to understand the research background of EV motor applications. In addition, the problem statement of this research is explained in detail, which the research objectives were based on. At the end of this chapter, the research outline is constructed into the listed chapters.



## 1.2 Research Background

The growth of electric vehicles (EVs) around the world is rapidly increasing in the past ten years, with the global stock of electric passenger cars passing 5.1 million units in 2018, an increase of about 63% from the previous year. As reported by the International Energy Agency (IEA), China showed an increasing number of electric car usage at a total of 2.3 million units, which was around 45%, compared with 39% in 2017. In addition, the electric car usage in Europe accounted for 24% of the global fleet and the usage was 22% in the United States [1]. The consumption of electricity could increase in the coming years due to EV usage. The IEA's New Policies Scenario 2030 stated that demand will continue for electricity, which is projected to reach almost 640 terawatt-hours (TWh), with light-duty vehicles (LDVs) as the largest electricity consumer among all electric vehicles. The share of electricity consumption by the electric motor driven system (EMDS) could be the largest based on the statistics in the IEA 2006 report, with 39% of consumption in the transportation sector [2]. Therefore, alternative ways should be explored globally to reduce electricity consumption by improving the speed-tracking accuracy of electric motors to give more mileage during driving.

There is an increasing trend in EV research, which shows the importance of taking care of the environment. EVs are a key technology to reduce air pollution in densely populated areas and it is a promising option to contribute to energy diversification and to reduce greenhouse gas emissions. EV benefits include zero tailpipe emissions, better efficiency than that of internal combustion engine vehicles, and a large potential for low greenhouse gas emissions. All these advantages are achieved by improving the EV speed even on rough road surfaces. Therefore, electric motors in EVs, such as the induction motor (IM), are commonly studied and widely developed to give extra efficiency during motoring [3].

The IM was patented in 1888 by Nikola Tesla and the structure was extended in 1890 by Dolivo Dobrowolski, which is known as the squirrel-cage motor [4]. IMs are mainly used in many industrial applications for requiring constant speed. In the past decades, DC motors are commonly used for variable speed applications. In the early 1990s, with advancements in power electronics and microprocessors, the characteristics of the IM have more advantages over that of the direct current (DC) motor as controlling methods are widely developed [5]. The advantages of the IM, such as high efficiency, simple construction, small in size, high reliability, and low cost, are the reasons why IMs are the most preferred machine in industries [6] and also in EV usage. Therefore, this has attracted more researchers to develop controllers for the IM due to its wide use as EV motors. Figure 1.1 shows the electric motor control system that is frequently used for improving motor speed control.

For power converters, the most efficient method of controlling output voltage is to incorporate the pulse-width modulation (PWM) control in the inverters. PWM is a way to control analogue devices with a digital output. A fixed DC voltage, such as the battery storage as in EVs, is applied to the inverter, and a controlled AC output voltage is obtained by adjusting the ON-OFF periods of the inverter devices [7]. The PWM-based variable speed drive is widely developed and used in many industrial and EV applications that require superior performance. There are various types of switching control techniques, such as PWM, Sinusoidal PWM, Multi-PWM, Modified Sinusoidal PWM, and Space Vector PWM (SVPWM) [8]. There is an increasing trend in using SVPWM due to its advantages of providing a more efficient switching control and better output and at the same time reducing the harmonic content in the voltage and increasing 15% of the fundamental output voltage [9]–[11].

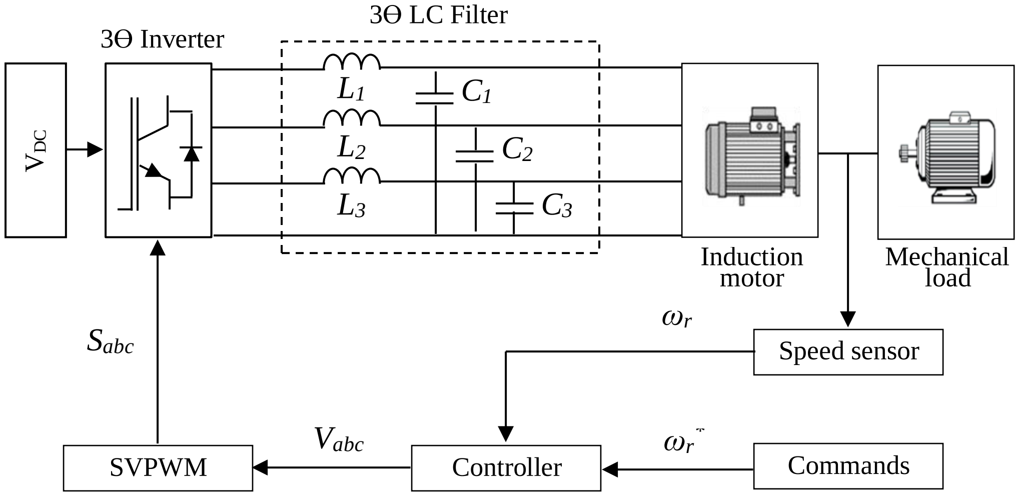


Figure 1.1: Electric motor drive system.

In an EV's mode of operation, during the motoring of an EV, speed and torque sensors are the main parameter inputs that will determine the speed, stability, precision, and power flow of the motor. Therefore, these sensors should be always in a healthy condition at all times regardless of the condition of the road. Currently, speed and torque sensors are used to regulate the performance of the EV in order to give good dynamic responses of especially the torque and speed of the EV. However, these sensors are relatively high in cost and very sensitive to road conditions. Therefore, this research aimed to develop a sensorless dynamic Indirect Field-Oriented Controller (IFOC) for the EV motor during road driving. The improved controller was tested on constant torque and varying torque in order to mimic road conditions. The biggest challenge was when the EV is in the motoring mode on un-flat surfaces, where the dynamic of the motor changed frequently. Therefore, it was necessary for the EV to give a continuous regulated speed to maintain motor efficiency.

In order to develop this sensorless dynamic IFOC controller, the estimated speed and hybrid fluxes were required as the feedback for the speed and current controllers. So, an improved estimator-based adaptation mechanism on hybrid stator flux controllers was designed to represent a sensorless speed signal to eliminate the use of the sensors in order to reduce the cost of the EV. To control speed behaviour, a special speed controller was designed in this research by implementing the artificial neural network (ANN) method to create the least error of speed with better dynamic speed performance. Together with the speed controller, a current controller was also placed to control the voltage regulated for the SVPWM input.

At the end, these two improved controllers (ANN hybrid flux estimator with the adaptive mechanism and speed controller) were tested in the MATLAB/Simulink platform for several cases for verification. Using these techniques, the controllers were able to increase the speed-tracking accuracy in the variable speed operation without being affected by parameter variations, such as resistance and inductance, and had a fast load disturbance rejection created by un-flat road conditions.

## 1.3 Problem Statement

Generally, the IM in EVs operates at the rated parameters of speed and load torque and at the rated efficiency. In some applications, variable speed is required due to the variable loads of the IM. In order to face these challenges, IMs that operate with variable frequency drives (VFDs) have been widely developed. However, in an EV, the IM is very sensitive to vibrations when the EV is moving on an un-flat road. This vibration will reduce the efficiency of motor performance. The biggest problem is that when the vibration gets stronger, the torque and the speed of the motor will not follow the rated values. Therefore, this will increase the deviation of the allowable boundary of IM response, especially the speed output, which then requires more power from the EV battery. This problem happens especially during driving on un-flat surfaces.

There are two strategies that can be used to overcome the problem, which are the Field-Oriented Control (FOC) and Direct Torque Control (DTC). However, by using DTC, the torque ripple needs to be between the boundaries of the allowable torque ripple. A torque ripple value that is more than the allowable value will affect the efficiency of the motor, especially the speed, and cause uncomfortable driving. While a constant torque is ideal, torque changes all the time when the EV is motoring or braking on un-flat road surfaces. This affects not only the speed but also the dynamic of the IM by causing the IM to absorb extra unnecessary power from the EV battery.

For FOC, there are issues, including cost, in controlling the IM. Usually, sensors are used to obtain the flux and speed of the IM, such as the optical sensor and tachometer. However, the use of sensors will increase the cost of motor control. Furthermore, there is complexity in placing sensors in the motor, which need more cables. In addition, regular maintenance is also required, making the cost of using sensors more expensive.

In order to solve this problem, this research proposed a hybrid model of flux and speed estimator, which was based on the voltage model and the rotor-flux-oriented current model, with an ANN-IFOC adaptive mechanism. The hybrid estimator used the principle of back-emf error compensation to minimise the speed error fed to the ANN-IFOC speed controller. It also aimed to increase speed-tracking accuracy, efficiency, and speed response and have a faster rejection of load disturbances.

## 1.4 Research Aim

The aim of this research was to establish an improved speed-tracking accuracy of a sensorless IFOC drive system for EVs during un-flat road driving by applying neural networks in sensorless hybrid flux and a speed estimator with an adaptive mechanism to minimize the speed error based on the principle of back-EMF error compensation.

## 1.5 Objectives



This research work embarked on the following objectives:

a) To investigate the sensorless dynamic IFOC of the IM drive by modelling it in MATLAB/Simulink based on the voltage model's flux and speed estimator.

b) To design an improved sensorless drive system for EVs on un-flat road conditions using the proposed hybrid flux and speed estimator to minimise the speed error fed to the speed controller.

c) To apply neural networks in the proposed ANN-IFOC hybrid flux and speed estimator to enhance the speed-tracking accuracy of rotor flux position for the speed controller.

d) To compare with the existing PI speed controller model the effectiveness and robustness of the proposed speed controller with ANN-IFOC hybrid flux and speed estimator towards speed-tracking accuracy improvements of the drive system.

## 1.6 Research Scope

This research focused on the dynamic performance of the IM of EVs for better speed-tracking accuracy, which is affected by the load torque variation of un-flat road conditions. The scope of this research is as follows:

a) Simulation model development:

- A dynamic IFOC controller in sensored and sensorless modes was developed, simulated, and tested in MATLAB/Simulink by using the SimPower library.
- The IFOC used a 5kHz three-phase IGBT inverter triggered with space vector pulse-width modulation (SVPWM).
- The control drive system used 800 V of DC source as the input voltage or battery storage behaviour.
- An LC filter was used to filter out the AC voltage of the inverter.
- The EV motor control in this research focused on a two-seater electric car based on the Renault Twizy model with a limit of 20-horsepower (Hp) induction motor.
- The performance of the EV in this research was scaled at the top speed of 80 km/h with 150 km of driving range and 3.5 hours of charging time.
- The capacity of the battery packs in this EV was rated at 12 kWh based on the lithium-ion material.
- The number of cells used were 20 cells rated at 2.45 V each with the arrangement of five modules.
- The real-condition test was conducted through a simulation with real parameters of the EV, in which the total mass was 690 kg and 4 tires with radius of 0.1651 m were used.
- The design of the speed bump used real data obtained from the Malaysian Public Works Department (*Jalan Kerja Raya (JKR) Malaysia*), which were 75–150 mm and 75–100 mm for the height and

less than 1 m and 2.2–4 m for the width of the road bump and the road hump, respectively.

b) Hybrid estimator and controller program development:

- A conventional speed controller was designed using the PI controller with a saturation limit.
- Two inner-loop current controllers were designed using PI-controller-based pre-compensated back-EMF.
- To deal with parameter sensitivity, an enhanced ANN-IFOC hybrid flux estimator was proposed with the 2-10-2 network topology using the back-EMF error compensation technique to estimate the flux based on stator current and voltage from the terminal of the IM.
- An ANN-IFOC speed controller was designed with the 2-10-1 network topology to deal with the variation of operating speed conditions and load torque disturbances.

## 1.7 Research Contribution

The proposed technique aimed to give special control to the IM by using the ANN-IFOC hybrid-flux-based adaptive mechanism with a speed estimator so that the IM could increase its speed-tracking accuracy. The approach was specifically based on back-EMF error compensation. It aimed to increase speed tracking by extracting accurate rotor flux position to achieve decoupled control of flux and speed. The proposed ANN technique in the estimator with the speed controller would reduce the speed error through the learning of the network so that it can adapt to the EV motor's behaviour. The operating condition of the IM could be longer with excellent performance obtained by the proposed method. Therefore, the increasing current trends of the use of artificial intelligence should be applied in all areas of research, as it benefits society.

## 1.8 Thesis Outline

This thesis presents a review of previous research and the design and analysis of the proposed ANN-IFOC hybrid flux estimator and speed controller of the EV motor drive. The thesis is divided into seven chapters and each chapter is summarised as follows:

**Chapter 2** gives an overview of previous research on the controlling methods of the IM. The basic principle of the IFOC concept was generally presented involving the dynamic modelling of the IM. Various methods for designing the estimator and the speed controller commonly used in previous research were widely covered in terms of the dynamic performance of the IM. Both conventional and modern techniques were compared through the research gap as a guide in proposing a better and more robust controller. Since ANNs were proposed in this research, the fundamental design of this method was studied in detail and several algorithms being used to design ANNs were gathered.

**Chapter 3** presents the steps in developing the complete system of the proposed drive through the proposed algorithm. The ANN method implemented in the hybrid flux estimator and speed controller was based on the backpropagation algorithm in a multilayered structure. The scheme of the Levenberg-Marquardt algorithm was explained for the offline training of the ANN hybrid-flux-estimator-based adaptive mechanism and speed controller to give the best feedback response. Also presented was the estimation of flux and speed by the proposed hybrid flux estimator based on the combination of the modified voltage model, which was compensated by the rotor-flux-oriented current model, with the ANN stator flux control as the adaptive mechanism for back-EMF error compensation. Together, the conventional proportional-integral (PI) current controllers with pre-compensated back EMF were discussed as the inner-loop control. The design flow was constructed via the flowchart at the end of the chapter to give a clear understanding of the control process.

**Chapter 4** presents the implementation of the sensorless IFOC drive system in MATLAB/Simulink. The sensorless drive system was investigated through two general cases to investigate the robustness of the estimator and the controller. Here, the decoupled control between flux and torque was achieved through the simulation results obtained. A table was provided to indicate the speed-tracking accuracy achieved.

**Chapter 5** presents the neural networks' performance of the proposed hybrid flux estimator and the speed controller. The ANNs' performance was analysed based on several stability plots to investigate network errors. The hyperparameters in the networks, such as weights and biases, were recorded in a table. These hyperparameters were responsible to make the networks adapt to the input model. Then, a summary was given to show the network parameters used in the applied neural network model.

**Chapter 6** presents the simulation results of the proposed ANN-IFOC hybrid flux estimator with an adaptive mechanism. Various cases were examined to verify the robustness of the proposed estimator. Back-EMF error compensation was explained based on the mesh plot graph. The estimated rotor flux and speed were presented through the data obtained. Comparison tables were tabulated to show the improvements achieved in the proposed model compared with the conventional model.

**Chapter 7** concludes the main objectives, findings, and contribution of this research, and recommendations were stated for future work of research.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

This chapter aims to give a clear development of EVs, which faces several issues in recent years, and also an overview of the development of IM control using various controlling methods during the late and modern eras of technology. The fundamental knowledge of IM modelling involving variables' transformation with respect to frames is described. Various models for the estimation approach of motor variables that were implemented in previous research works are presented. Another important part in this chapter is a review of speed controller designs based on previous research, where conventional and modern techniques are compared for a better and more robust controller. Since AI was explored in this research, the fundamental knowledge of ANNs is described in detail and several algorithms used to design ANNs are gathered.

## 2.2 Current Issues in Electric Vehicle for Future Transportation

Economic and environmentally friendly, electric vehicles have grown in popularity considerably in recent years. The increasing trend in electric car registration indicates people's interest in choices of future transportation. The electric light commercial vehicles (LCVs) globally are stated at 435,000 units, a third of which are in Europe, where new electric LCV registrations in 2020 were only 5% below those in China, which is the world leader [12]. However, these increasing trends come with some issues facing EV production. So, EV automakers should take actions to overcome some hurdles before EVs are broadly adopted.

A common issue related to EVs raised by customers is the driving range. The driving range differs based on the size of the EV. It also depends on the speed limit of the EV. The speed limit for a small EV is in the range of below 80 km/h. For the Toyota C+pod electric car roughly calculated for 150 km of range, the EV needs a 6.1 kWh battery pack for a single electric motor. But, for the top speed of 60 km/h, it requires a motor rating of 12 Hp [13]. So, a larger battery capacity is needed for a longer driving range.

However, the issue regarding larger battery capacity is that more space is needed for the EV. Hence, it is hard to produce a small EV with a longer driving range. An optimum space in a small EV is needed to store the number of cells according to its module in the battery packs. Furthermore, this depends on the type of battery material. Current trends show that Li-ion batteries are widely used due to specific advantages, such as having more energy density and cycle durability, as shown in Table 2.1.

Table 2.1: Characteristics of EV batteries [14].

| Characteristics of EV batteries | Type of EV batteries | | | | | | |
|---|---|---|---|---|---|---|---|
| | $Pb\text{-}PbO_2$ | Ni-Cd | Ni-MH | $Zn\text{-}Br_2$ | Na-NiCl | Na-S | Li-Ion |
| Working temperature (°C) | -20-45 | 0-50 | 0-50 | 20-40 | 300-500 | 300-350 | -20-60 |
| Specific energy (Wh/kg) | 30-60 | 60-80 | 60-120 | 75-140 | 160 | 130 | 100-275 |
| Energy density (Wh/L) | 60-100 | 60-150 | 100-300 | 60-70 | 110-120 | 120-130 | 200-735 |
| Specific power (W/kg) | 75-100 | 120-150 | 250-1000 | 80-100 | 150-200 | 150-290 | 350-3000 |
| Cell voltage (V) | 2.10 | 1.35 | 1.35 | 1.79 | 2.58 | 2.08 | 3.60 |
| Cycle durability | 500-800 | 2000 | 500 | >2000 | 1500-2000 | 2500-4500 | 400-3000 |

Logically, EV automakers mostly focus their sales in cities with people using EVs as the main short-range transportation. In addition, the use of EVs depends on the availability of EV charging stations, which are commonly in cities with a huge population. So, the demand for EV charging is the biggest challenge for automakers, since a wide network is needed to place EV charging stations at landmark buildings. Besides that, EV charging stations are costly. Moreover, charging time is also an important factor. But this depends on the capacity of the battery. Current technologies could be the main support for EV supercharging stations to be realised, which needs more research.

In producing an EV, the size of EV is one of the main factors related to the target users and areas. It is affordable to produce small EVs for transportation in areas with good road conditions. Bad road conditions could affect the most important part of an EV, which is the motor, the lifespan of which could be short. Poor or bumping roads may affect motor operation at the side of motor load. Hence, maintenance cost has to be considered to maintain EV motor performance. Alternatively, the EV motor could be given special control to operate on poor roads or bumping roads so that the motor could withstand variable motor loads.

Currently, several new technologies are implemented today, and still some to be evaluated, in order to increase EV performance. Users need a lot of consideration to use their own EV for daily routine, since it involves specific costs. However, using EVs as the main transportation could maintain a green environment. When the issues are narrowed down, electric motor control is qualified to be investigated for future development, as listed in Table 2.2. In the table, the highest score for each motor's characteristics is 5, representing the highest power density, efficiency, controllability, reliability and technological maturity, and the lowest cost.

Table 2.2: Types and characteristics of electric motors in EVs [15], [16].

| Index | Propulsion system | | | |
|---|---|---|---|---|
| | DC | IM | PM | SRM |
| Power density | 2.5 | 3.5 | 5 | 3.5 |
| Efficiency | 2.5 | 3.5 | 5 | 3.5 |
| Controllability | 5 | 5 | 4 | 3 |
| Reliability | 3 | 5 | 4 | 3 |
| Technological maturity | 5 | 5 | 4 | 4 |
| Cost | 4 | 5 | 3 | 4 |
| Total score | 22 | 27 | 25 | 23 |
| Common brand | • PSA Peugeot-Citroen<br>• ZAP Xebra<br>• NICE Mega | • Tesla model X<br>• Tesla model S<br>• Mercedes-Benz EQC<br>• BMW X5 | • Tesla model 3<br>• BMW i3<br>• Toyota Prius<br>• Mitsubishi i-MiEV | • Land Rover<br>• Holden Eco |
| Advantages in EV | N/A | • Competitive efficiency against PM at high speeds on torque speed curve.<br>• Possible efficiency optimisation with control of flux.<br>• Economical due material cost. | • Reduces total weight of vehicle.<br>• Lower current rating for inverter and improved battery utilisation. | N/A |

*Notes: DC: Direct current; IM: Induction motor; PM: Permanent magnet; SRM: Switch reluctance motor; N/A: Not applicable.*

## 2.3 Theory of 3-Phases Induction Machine

The most widely used AC machine is the induction or asynchronous machine due to its advantages, such as being rugged, reliable, and economical. It can be used as both a motor and a generator, like any electrical machine. The induction of the machine is when the stator winding produces a spinning magnetic field that causes the short-circuited rotor winding to alternate.

In general, the induction machine consists of two parts: the stationary component, called the stator, and the rotating cylindrical part, called the rotor. Both the stator and rotor irons are made up of laminate cuts from iron sheets a few tenths of a millimeter thick. This is to minimise iron losses caused by the alternating magnetic fields (hysteresis and eddy currents) [17]. The laminations of the stator are slotted to allow a three-phase winding on the inner surface. Coils of multiple turns scattered over the periphery of the stator comprise this winding. The coils of each step are linked in sequence. An acceptable spacing of the coils (pole pitch: 180° for 2-pole motor, 90° for 4-pole machine) achieves the desired number of poles and the associated speed/frequency. The stator of an induction machine with four poles rotates at 1500 *rpm* of synchronous speed with 50 Hz of fundamental frequency [18]. The ends of each coil are directed to the terminal box and can be attached to the three conductors of the network in either star or delta, as shown in Figure 2.1. The stator winding consists of overlapping winding represented by $L_a$, $L_b$, and $L_c$, which are offset by an electrical angle of 120°. When the stator winding is connected to a three-phase AC source, magnetic flux is induced, which then creates electromagnetic voltages $e_a$, $e_b$, and $e_c$. Depending on the need for torque or speed control, the rotor winding configuration differs. It is possible to differentiate between two general categories, which are the squirrel-cage rotor and wound rotor.

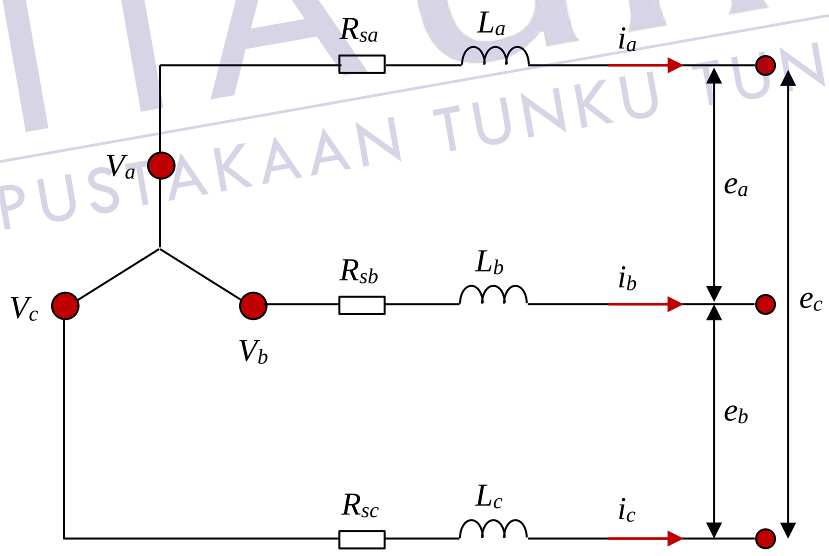


Figure 2.1: Three-phase configuration of IM at stator side [19].

## 2.4 Adjustable Speed Drives

The electric motor was first developed in the 1830s, 30 years after the invention of the first battery. Interestingly, the motor was developed before the first dynamo or generator was invented. The development of electrical drives began in 1834 when the electric motor was developed by Thomas Davenport based on the principles of electromagnetic fields introduced by Joseph Henry and Michael Faraday in 1821 [20]. This developed technology used Faraday's law and Fleming's law. The development of electric drive in induction motors was continued by Nikola Tesla in 1888.

The advancement in the electric drive is much related to the technological development of power semiconductor devices. Before semiconductors were developed, DC motors were widely used to obtain variable speed due to fast torque and easy decoupled control between the flux and torque components [21]. Flux and torque are always magnetically perpendicular to one another. Torque is controlled via armature current while maintaining the field component constant. However, regular maintenance is required due to the mechanical construction of the commutator and brushes, which limits speed, making DC motors suitable for preset speeds. In contrast, in an induction motor, a fixed speed is applied due to the fixed frequency and voltage supply. However, some actions are manually taken to control the speed of the IM by generating an alternating-current (AC) voltage with variable frequency using rotary converters, which are bulky and inflexible [22]. Poor results are obtained and, consequently, DC drives have been widely used.

After the development of power semiconductors, such as the bipolar junction transistor (BJT) in 1950 and the silicon-controlled rectifier (SCR) in 1957, it became possible for power semiconductors to be used in a static converter or inverter for high-power applications [23], [24]. AC motor speed can be controlled because variable AC frequency can be generated using inverters. In the early 1960s, the fabrication of BJT with pulse-width modulation brought new contributions to the AC motor. With complex algorithms, high performance of torque control of the AC motor was nearly achieved similar to DC drives but there was a complex magnetic coupling between the phases in the stator and rotor of AC machines.

The development of adjustable speed drive (ASD) or variable speed drive (VSD) was rapid until the early 1980s, where the revolution of microprocessors contributed to modern complex algorithms as a more effective way to develop variable-speed AC machines due to the advantages of AC machines, such as having no commutators or brushes and requiring no maintenance. These advantages make AC machines being exploited in the applications of high variable speed compared with DC drives. The trend of using adjustable speed drive has increased in industrial, utility, and agricultural fields. ASDs control the speed of the machinery in some applications. Many industrial processes, such as assembly lines, must operate at different speeds for different products. Process engineers had been asked for the ability to control the speed of machines according to variable production. It is where process conditions demand adjustments, such as the flow from a fan or pump, to vary the speed of the drive to save energy and cost. This principle can be applied in many applications, such as EVs, where this environmentally friendly technology is developed worldwide.

Generally, ASDs can provide a reliable dynamic system that significantly contributes to the minimum energy usage and low cost of IM operation. Obtaining the accurate speed of the IM is an important requirement for ASDs for robust and high-precision control. As shown in Figure 2.2, ASDs offer two approaches in controlling electric motors, which are scalar and vector controls.

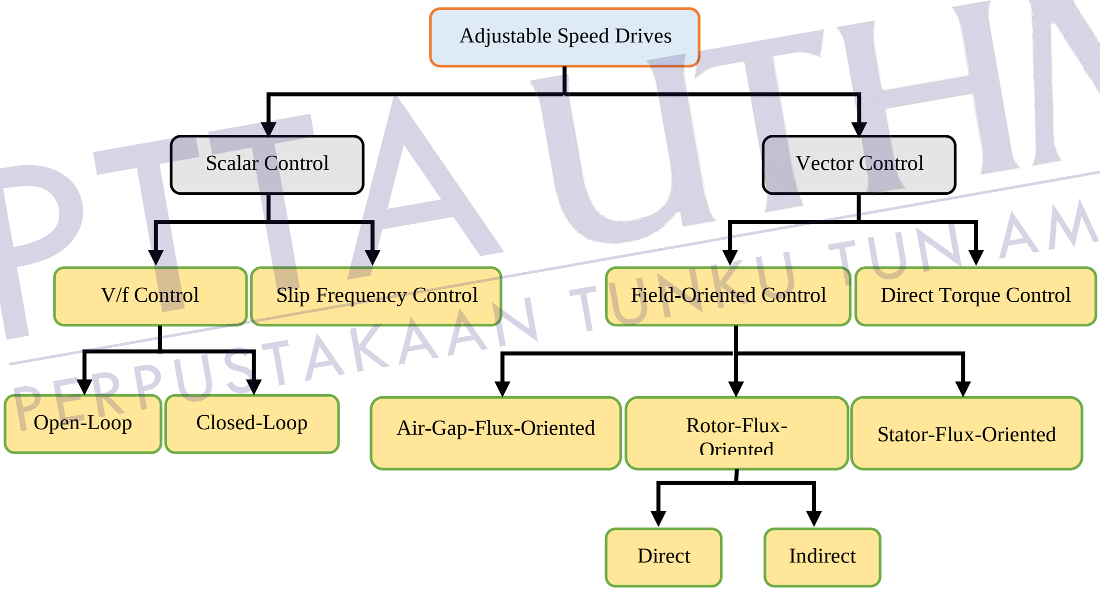


Figure 2.2: Adjustable speed drives (ASDs) of IM.

### 2.4.1 Scalar Control of IM Drive System

Most existing variable speed drive systems with induction motors are low-performance drives, where the adjusted variables are the magnitude and frequency of either the voltage or the current supplied to the stator. This allows control of the motor’s steady-state speed or torque while the motor’s magnetic field is held at a desired constant level. This form of control is commonly referred to as scalar control because the controlled stator voltage or current is presumed to be sinusoidal and because the system operates with only the adjusted magnitude and frequency and with no regard for the spatial location (phase) of the corresponding vector quantities. Scalar control systems are simpler than those using vector control, but the latter's superiority is unquestionable due to the drive's complex output.

The first controlling method via scalar control used in practice was constant voltage/hertz (CVH), also known as V/f control. This control scheme involves the adjustable magnitude of stator voltage and frequency to be fed to the induction motor. The principle of this scheme is based on maintaining the air gap flux at a constant value at steady state so that the ratio of V/f remains constant by controlling stator voltage and frequency [25]. This scheme focuses on the steady-state dynamics, which allow the stabilisation of stator flux with different speed and torque values. In order to a maintain constant flux level, the voltage should be increased when frequency increases, and vice versa. As V/f is kept constant, this scheme is called the variable voltage/variable frequency (VVVF) method.

The most common scheme of V/f control and widely used in industries is the open-loop control due to its simplicity, which was proposed in [26] and [27]. However, it encounters some problems, such as a sluggish response and the systems are easily exposed to instability because of the effect of the higher-order system. This technique is usually used in low-speed applications, where speed control is not necessary because the speed cannot be controlled precisely [28]. In this scheme, rotor speed is not measured, causing the slip not maintained. Hence, the torque-speed characteristics may operate in an unstable region, causing stator current to exceed the rated current and become harmful to the inverter-converter combination [29], [30].

Lately, advancements in power electronics and microprocessors are able to increase motor performance. Variable frequency and variable voltage are used increasingly in various applications to provide constant air gap flux so that voltage is frequently varied and machine saturation problems, as faced in [31], are avoided. Therefore, another way to improve open-loop V/f control is controlling the system using a closed-loop scheme, which offers a more precise solution of speed control compared with that of open-loop V/f control, as proposed in [32]–[34], where a PI controller was used to control speed. However, the voltage drop across stator resistance is ignored, making speed control in the low-speed region not being fully satisfied. It is where the torque response takes a lot of ripples even though the scheme fully applies voltage compensation to boost speed control in the low-speed region, as shown by the voltage profile in Figure 2.3.

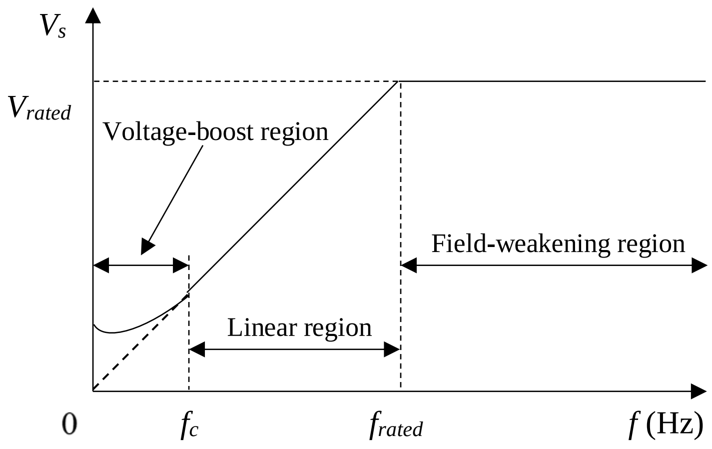


Figure 2.3: Stator voltage versus frequency profile under V/f control.

Alternatively, torque can be controlled, which is also not done in the open-loop scheme, by also using the maximum torque per ampere (MTPA) control strategy, as proposed in [35] and [36]. In this scheme, stator voltage, supply frequency, and slip power recovery can be controlled by this scalar control method in controlling the speed of the induction motor. Hence, the most popular scheme currently used in the scalar control method is the closed-loop V/f control, where the supplied voltage and frequency are varied to keep the V/f ratio constant. The closed-loop V/f control, as shown in Figure 2.4, used a PI controller, where the speed controller interacts with a V/f control scheme called the slip-based VVVF speed controller. The speed controller's output is regarded as torque command, and the required slip is calculated in proportion to the torque command. The synchronous speed is determined by the addition of slip and measured rotor speed, where it acts as the command frequency for the VVVF inverter. However, the controlling operation is not very stable and the IM can easily lose synchronisation in the high-speed region or under abrupt load changes [37].

Based on Figure 2.3, at a higher rated frequency, the V/f ratio cannot be satisfied because it will lead to the field-weakening region due to insulation breakdown at stator windings. This is the main factor that limits the V/f control to the ratio when the rated frequency is reached. In order to have a stable operation in the high-speed region, stabilising loops are introduced based on power calculation [37]–[39]. However, there are large overshoots in the speed response during load changes. Also, the phase current's angle and the estimated rotor position's angle are larger compared with those in the low-speed operation. This show that there are higher stray and friction losses at higher frequencies in the high-speed region, as examined in [40].

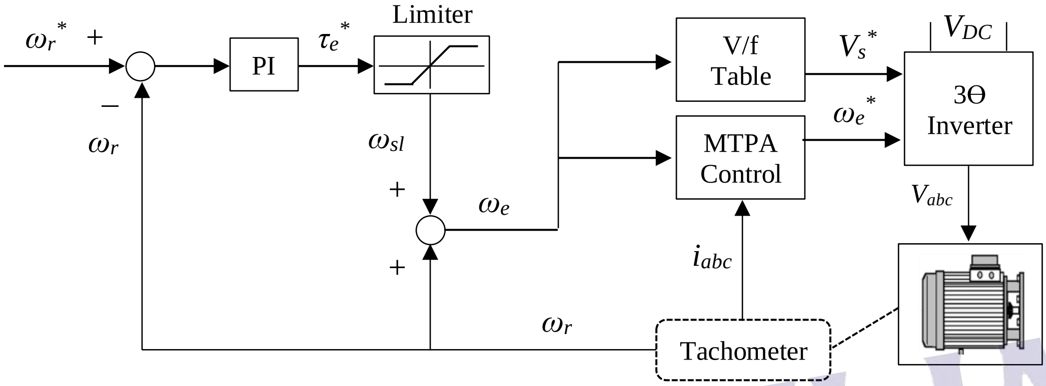


Figure 2.4: VVVF pattern and slip-based VVVF speed controller with MTPA.

Both open-loop and closed-loop controls of the speed of the AC induction motor can be implemented based on the constant V/f principle. There are some advantages of the closed-loop control over the open-loop control that can be highlighted, such as the accuracy in speed response. However, previous studies faced challenges in solving speed control in the high-speed region, since the frequency is limited to give a stable operation. Due to these drawbacks, current research trends show that the development of vector control is widely explored and discussed. Attention has shifted towards various types of vector controls in order to solve the problems faced in the scalar method especially on the variable speed response and load changes in the stable operation region.

### 2.4.2 Vector Control of IM Drive System

The development of VSDs is currently increasing by introducing more effective ways of control operation using vector control and consequently eliminates scalar control. This type of control offers better dynamic performance than scalar control due to special characteristics. It has a different operation than those in previous controls, where torque and flux are controlled by controlling the stator current fed to AC machines. The objective of this control is to emulate the behaviour of a separately excited DC machine in order to achieve decoupling between torque and flux of the IM with respect to the reference frame [41]. As in DC machines, the magnetic field and torque are directly and independently controlled by the field and armature currents. In AC machines, stator current components are the fundamental contributor in establishing magnetic field and electromagnetic torque production. The field flux produced by the field current is orthogonal to the armature flux produced by the armature current, giving rise to the most favourable condition for torque production.

The principle of vector control is the conversion of three-phase stator currents into corresponding complex space vectors. The current vector is then transformed into a coordinate system rotating with the rotor of the machine [42]. In order to have decoupled control of flux and torque, rotor positions must be known. Basically, the speed variable is selected and measured by using a speed sensor. Then, the rotor flux linkage vector is estimated by the product of stator current and magnetising inductance. By using the rotor flux linkage, the stator current vector is further transformed into a *d-q* coordinate system to control flux and torque.

In vector control, various control strategies are introduced based on the functionality of the motor system. The implementation of this control can be done in many ways but several basic schemes are widely used and offered in the market. The most popular vector controls are field-oriented control (FOC) and direct torque control (DTC), which have become evolutionary methods and are widely used in current research works.

#### 2.4.2.1 Direct Torque Control (DTC)

Direct torque control (DTC) was presented by Isao Takashi and Toshiko Noguchi in 1985 with a similar concept that was patented by Manfred Depenbrock (U.S. Patent 4, 678, 248) in October 1984 called direct self-control (DSC), and it has the same objective as that of field-oriented control (FOC), which is to control the torque and speed of three-phase AC electric motors. DTC alleviates the step of intermediate current synthesis by directly linking stator voltage to the torque and flux of the machine. Recently, DTC is implemented in different ways. The conventional DTC is based on the hysteresis controller of torque and flux that results in variable switching frequency for power electronic converters. The principle is to have direct control of the inverter state while simultaneously maintaining stator flux and torque within the hysteresis band limits. Hence, this type of control avoids the use of the current control loop.

A hysteresis controller operates by passing the difference between the evaluated amount and command amount of flux and torque to the inverter. Flux and torque of the IM are usually estimated by using a block of estimator. If either the estimated flux and torque deviates from the reference more than allowed tolerance, the switching frequency is turned off and on so that flux and torque return to their tolerance bands as quickly as possible. Acting like a comparator, the controller works in different levels, where the torque section consists of three levels, while the flux consists of two levels because stator flux cannot be held constant during motor operation, as shown in Figure 2.5. The advantage of this control, commonly mentioned in previous studies, is that there is no rotor position required to attain the decouple variables [43].

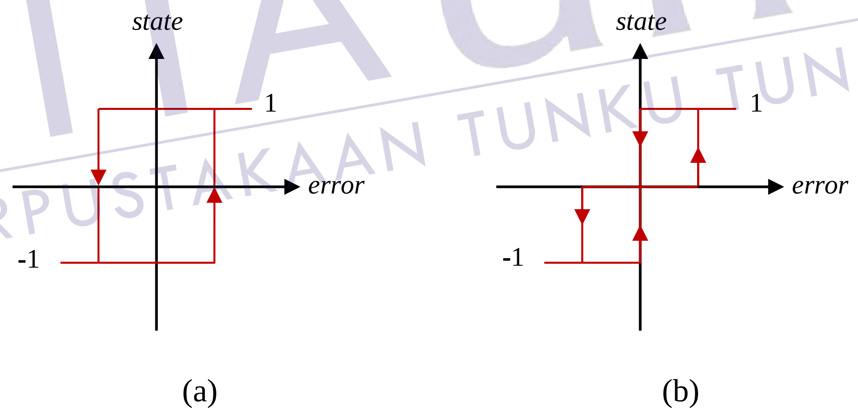


Figure 2.5: Hysteresis controller: (a) flux level and (b) torque level.

The configuration of a DTC-based hysteresis controller, as shown in Figure 2.6, is commonly used in previous research works to avoid a complex structure compared with those in other vector controls. Stator flux position is determined by the estimator directly syncing with torque and flux errors of the hysteresis controller as inputs to the switching table.

The stator flux position is divided into six different sections, listed according to their state, so that the three-phase inverter creates six non-zero and two zero-voltage vectors. The proper selection of voltage vectors based on the switching table is shown in Table 2.3. Based on the configuration, there are no coordinate transformations, PI regulators, PWM modulators, and position encoders required. Two loops of stator flux and torque are not enough to solve the issues faced in machine-control development, such as current distortion and good load disturbance rejection [43], [44]. Therefore, some modifications have been introduced based on this conventional scheme.

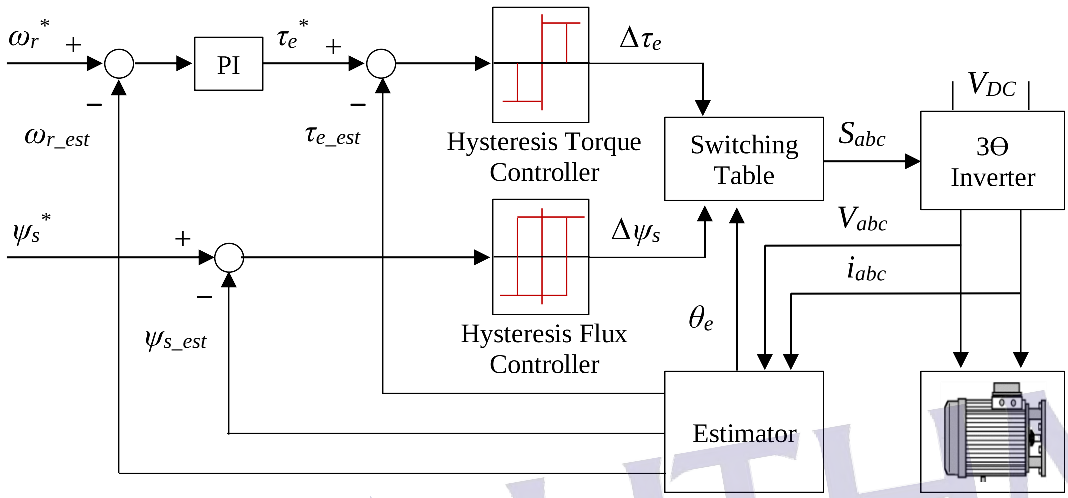


Figure 2.6: Block diagram of conventional DTC-based hysteresis controller of IM.

Table 2.3: Switching table for voltage vector in DTC.

| Stator flux, $\Delta\psi_s$ | Torque, $\Delta\tau_e$ | Stator flux position, $\theta_s$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ |
| 1 | 1 | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) |
| | 0 | $V_7$ (111) | $V_0$ (111) | $V_7$ (111) | $V_0$ (111) | $V_7$ (111) | $V_0$ (111) |
| | -1 | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) |
| 0 | 1 | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) |
| | 0 | $V_0$ (111) | $V_7$ (111) | $V_0$ (111) | $V_7$ (111) | $V_0$ (111) | $V_7$ (111) |
| | -1 | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) |

The DTC-based hysteresis controller has completely evolved with the implementation of DTC with constant switching frequency using voltage synthesis techniques, such as PWM and SVPWM. This technique resulted in improvements, such as fixed amount of switching losses and minimum harmonic distortion, as mentioned in [45]. The idea remains the same, where flux and torque controllers are compulsory by replacing the conventional PI controller. The configuration of DTC-based SVPWM for voltage synthesis, as shown in Figure 2.7, is composed of three controllers, which are PI speed, torque and flux controllers, with the implementation of SVPWM [45]–[47]. With this scheme, the response of the IM yields superior performance at steady state over a wide range of speeds. However, there are some drawbacks, such as high ripple torque and poor dynamic performance at low speeds [48]. In addition, a few research studies reported that errors in flux and torque are not distinguished [49], [50]. In other words, the same vectors are used during starting up and step changes and at steady state.

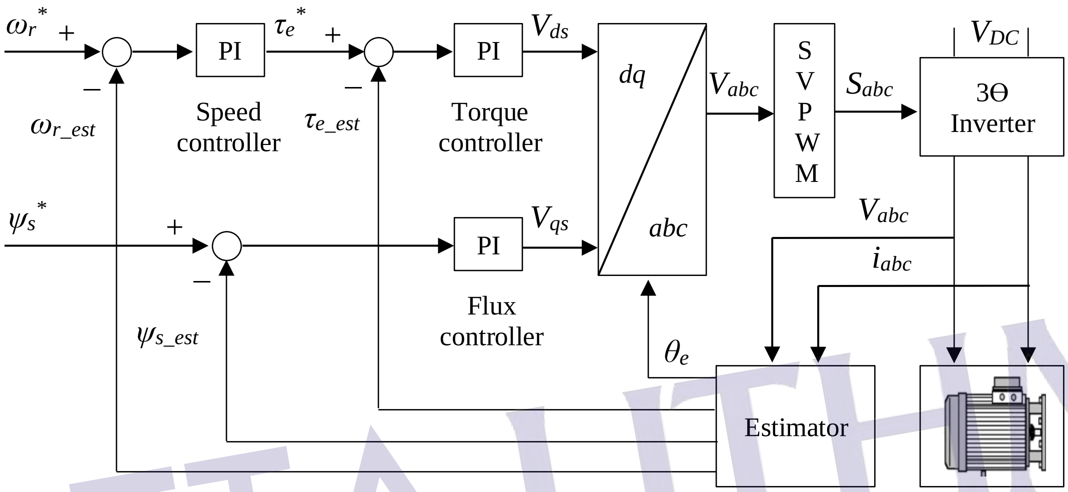


Figure 2.7: Block diagram of modern DTC-based SVPWM of IM.

As a rising control technology, DTC is commonly used due to its advantages, such as simplicity by not considering the internal parameters of IM, such as slip speed, rotor resistance variation, and EMF error effect. Hence, an evolutionary method is required to give special control characteristics to the IM. Therefore, field-oriented controls are widely developed and investigated to avoid the poor results from using DTCs.



### 2.4.2.2 Field-Oriented Control (FOC)

In AC machines, torque is expressed as the outer product of flux and current vectors. Therefore, maximising the torque value can be done by using the two vectors in orthogonal. In DC motors, the orthogonality is guaranteed by the brush and commutator actions. However, in AC machines, this can be achieved dynamically in the synchronous frame. There are two degrees of freedom, based on a balanced three-phase current system, allocated to two different missions, which are flux regulation and torque control. However, there is an unclear decomposition role according to the fixed coordinate frame. Thus, taking into synchronous reference frame, the roles of *d*- and *q*-axis currents are naturally decomposed and the dynamics resemble those of a separately excited DC machine.

Therefore, the field orientation concept is used to accomplish decoupled control of torque and flux. This concept is the same as that in a DC machine's direct torque control, which has these following requirements [51]:

- Independent control of armature current to overcome the effects of armature winding resistance, leakage inductance, and induced voltage.
- Independent control of the constant value of flux.

When all these requirements are met at every instant of time, torque will follow current. This allows for torque control and decoupled torque and flux. Further knowledge on the decoupled control's concept can be reviewed from the two-phase *d*-*q* model of an induction machine rotating at synchronous speed. For summarisation of the *d*-*q* model, some equations are included in **APPENDIX B**.

The FOC in an IM consists of controlling stator currents, where it is represented by a vector phasor, as depicted in Figure 2.8 [52], which projects the transformation of the three-phase quantities into two-coordinate *d*-*q* axes. Two constant inputs are required as reference, which are torque and flux. The torque component aligns with the *q*-coordinate, while the flux component aligns with the *d*-coordinate. It is simply based on transformation projection, as it handles the instantaneous electrical quantities by the control structure, which results in accurate control for every working operation, such as steady state and transient, independent of the limited bandwidth of the mathematical model.

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