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# Assessment of Control Drive Technologies for Induction Motor: Industrial Application to Electric Vehicle

A. Z. Ahmad Firdaus<sup>1</sup>, S. A. Azmi<sup>1</sup>, K. Kamarudin<sup>1</sup>, L.J. Hwai<sup>1</sup>, H. Ali<sup>1</sup>, M. S. Z. Azalan<sup>1</sup>, and Zamri Che Mat Kasa<sup>2</sup>

<sup>1</sup>Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis

<sup>2</sup>MSM Perlis Sdn Bhd, Perlis

ahmadfirdaus@unimap.edu.my

**Abstract.** Nowadays electric vehicle has increasingly gained much popularity indicated by growing global share market targeted at 30% by 2030 after recording 7.2million global stock in 2019. Compared to Internal Combustion Engine (ICE) counterpart, Battery Electric Vehicles (BEV) produce zero tailpipe emission which greatly reducing carbon footprints. Induction motor has been widely used and its control technology has evolved from scalar type volt/hertz to recent predictive control technology. This allows induction motor's application to expand from being the workhorse of industry to become prime mover in electric vehicle, where high performance is expected. Among vector control scheme, Direct Torque Control (DTC) has gained interest over Field Oriented Control (FOC) with simpler structure, better robustness and dynamics performance yet suffer from high torque and flux ripple. In electric vehicle applications, high ripple at low speed is highly undesirable, potentially causing torsional vibration. High performance control requires speed sensor integration, which often increase complexity in the design. The work aims to review the best control technology for induction motor in electric vehicle application through performance parameter evaluation such as improvement on dynamic response, torque and flux ripple reduction, and component optimization. Several arise issues in motor control and possible methods to circumvent are highlighted in this work. In conclusion, model predictive torque control (MPTC) is the most promising scheme for electric vehicle with excellent dynamic response, good low speed performance, and 50% torque ripple reduction compared to conventional DTC and potential integration with sliding mode observer for sensorless solution.

**Keywords:** Electric vehicle, model predictive control, direct torque control, induction motor

## 1. Introduction

In 2019, electric vehicle global car stock was recorded at 7.2million, an increase by 40% on yearly basis. Its global market share was targeted to increase to 30% by 2030 [1]. Compared to Internal Combustion Engine (ICE) counterpart, Battery Electric Vehicle (BEV) which is propelled by electric motor (also known as traction motor), using energy stored in rechargeable batteries produce zero tailpipe emission [2], greatly reducing carbon footprints by half in 2019 [1]. Both DC motor and AC motor have been used as traction motor. Series DC motors have been used as traction motor since 1900 due to high starting torque capability and ease of control [3]. However, its limitation includes low efficiency, tendency for heat build-up due to complications with brushes and commutator and lack of regenerative



braking capability [2]. AC motor that has less rotating component and offer flexibility in term of power recovering using regenerative braking. Three most popular types of AC traction motor used are induction motor (IM), permanent magnet synchronous motor (PMSM), and switched reluctance motor (SRM). Induction motor is preferred over PMSM due to lower material cost and over SRM due to higher efficiency [4].

In industrial applications, 90% of the motors employed are three phase induction motor type [5]. Simplicity, ruggedness, low-cost and ease of maintenance are the factors contributing to its popular selection in most industries ranging from palm oil to steel plant [6], [7]. They are primarily used to drive machineries such as conveyors, blower fans, pumps, and compressors. Formerly, they were only operated as fixed speed due to fixed supply nominal frequency. Compared to constant-speed drive, the variable speed operation is superior with higher efficiency, better energy savings and significant cost reduction through less frequent downtime [6], [8], [9]. In the sugar mills, speed control of centrifugal pump has resulted 50% energy savings through 20% speed regulation [10]. Control technology has evolved from scalar type – volt/hertz to recently developed predictive control. This has allowed induction motor application to expand from being the workhorse of industry to become prime mover in electric vehicle. Induction motor is used as prime mover in the current Tesla Model-S BEV[11].

This work is intended to provide some reference on technical aspect for researchers and industry player in selecting the motor control technology that best suits the electric vehicle application, within the purview relevant to induction motor. Through the review, parameters such as improvement on dynamic response, torque and flux ripple reduction, as well as component optimization are discussed and evaluated. This paper is organized in such arrangements: Section 2 highlights on the operational requirements of electric vehicle, Section 3 introduces the available motor control strategies, Section 4 discusses the performance analysis of motor control strategies based on application in electric vehicle and finally a conclusion.

## 2. Electric Vehicle Requirement

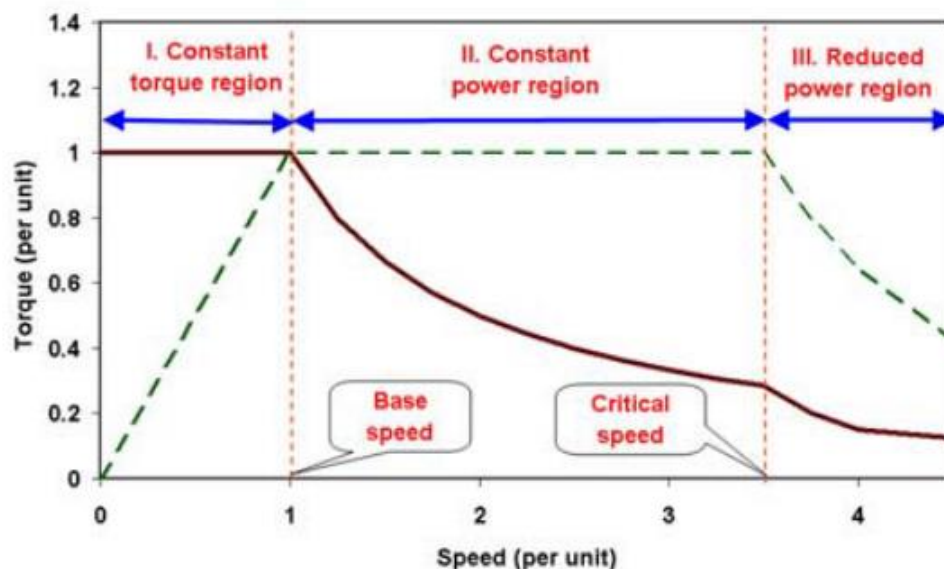


Figure 1 : Idealized torque / power – speed characteristics.[12]

Figure 1 shows the idealized torque / power – speed characteristics for electric vehicle. Electric vehicle may operate in the constant torque region at low speed up to rated speed (also known as base speed). At this range, optimum torque is generated where power increases in tandem with speed. Beyond rated speed, power limit is capped and thus, generated torque decreases as speed is further increased. This is due to flux generated-back electromotive force (EMF) exceeded maximum inverter output voltage and

therefore, field weakening is required to mitigate the effect [13]. It is highly desirable for electric vehicle to have high efficiency over wide operating speed range [12], [14] with a constant power operating range of around 3 to 4 times the base speed. This, combines with good battery technology provides high driving range which is essential requirement [3]. They are also expected to possess high torque density and high overload capability without compromising the need to have high fault tolerance and robustness appropriate to vehicle environment. High torque is essential for starting, at low speeds and hill climbing, while high power is useful for high-speed cruising [12]. However, cost have to be kept low at affordable range to tap the interest of middle-class consumers.

Motor ripple is also an issue in electric vehicle since it is the only active prime mover. Ripple poses adverse effects on motor output characteristics during low-speed drive and when operating at high torque. At high speed, the ripple effect would be cancelled by rotor inertia. It could cause torsional vibration causing vehicle to shake, especially when the ripple frequency match the resonant frequency of the system [15]. Motor ripple is partially caused by torque and flux ripple and could be due to side effects of control scheme employed in the drive system such as conventional Direct Torque Control [16]. Therefore, it is imperative that the ripple effect is minimized to ensure comfort of passenger and prolong the lifespan of vehicle components.

### 3. AC Motor Control Strategies: Theoretical and Practical Consideration

For induction motor, control technologies can be classified to two main categories according to control principle: scalar control and vector control.

#### 3.1. Scalar Control

In scalar control, main parameter of motor is varied directly so that output parameter such as position, speed and torque can be controlled. Two main types of AC induction motor are: wound rotor and squirrel cage.

For wound rotor motor, the rotor winding is connected to slip rings which, in turn, connected to external resistors. Variation of resistors have made speed control possible. However, the efficiency is relatively low because of high voltage drop across the resistors. Furthermore, this control method seems impractical with higher load conditions [3]. The alternative way to control is through implementation of pulse width modulation (PWM). PWM control is possible through inverter circuit and is feasible with operating nature of squirrel cage, which is why it is more popular than wound rotor.

In squirrel cage induction motor, variation of frequency of terminal voltage could be used to control torque and speed of motor. However, controlling only stator frequency with disregard of keeping fixed voltage/frequency ratio will deteriorate flux at the air gap. It resulted very high currents that would cause motor damage at very low frequency while at high frequency motor may be stalled. Hence, both frequency and voltage ratio need to be fixed in order to maintain constant torque when controlling speed. This method is also known as volt/hertz method [3].

Variable frequency drive in industry utilizes both open-loop and closed-loop control. For non-critical applications such as conveyors and centrifuge where low and medium speed operation at light and medium load, open-loop control is sufficient. Typical open-loop motor control drive system involves three phase inverter, driver circuit, the motor and connected load. The three phase AC supply is rectified to DC prior to be fed to the inverter. The inverter supplies variable frequency three phase voltage and current to the induction motor. The driver circuit consist of component that modulates the input signal in the form of Pulse Width Modulation (PWM) signal that triggers the inverter circuit [5].

Figure 2 shows previous design utilizing volt-hertz concept for open-loop control. The reference speed input combined with slip speed produce the command frequency. The command frequency is converted to corresponding voltage command through a volt-hertz profile that maintains relationship at approximately rated volt to frequency ratio [6]. For open loop, slip speed has to be estimated in the absence of speed sensor but with adequate induction machine model parameters, it is possible [17], [18].

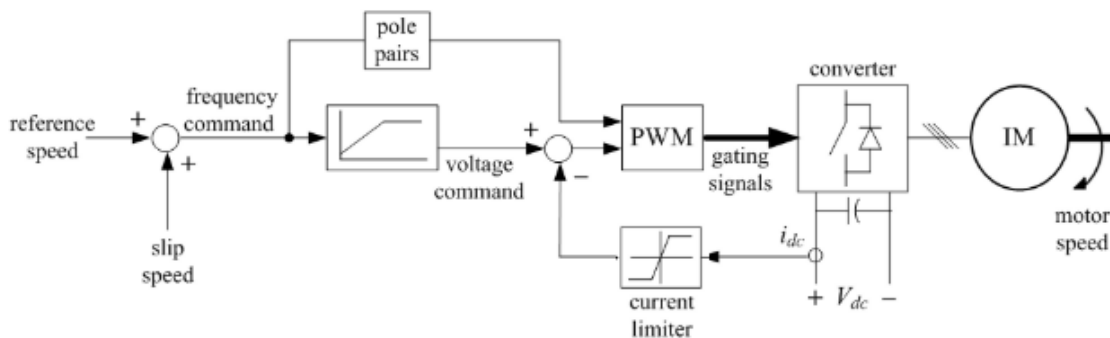


Figure 2 : Volt/Hertz open-loop control[17]

Closed-loop control offers better dynamic performance and is more suitable for critical applications. In closed-loop control, the system tracks the input pattern and automatically tune the parameter upon load variation or disturbance. With sensor feedback, slip speed parameter is more accurate. In [19], through comparison of reference and feedback speed, the error is fed to controller where the output is developed torque that can be converted to slip speed. Figure 3 shows Volt/Hertz closed-loop control using PI-controller.

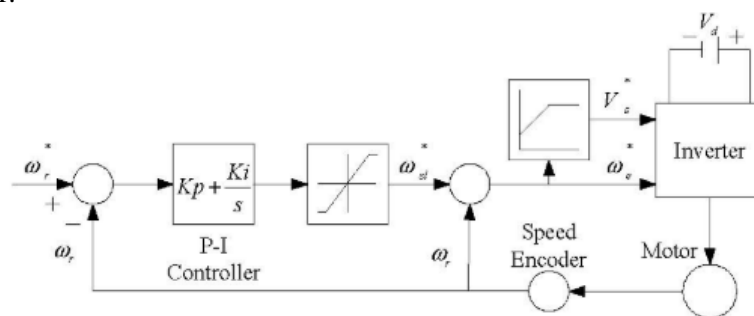


Figure 3 : Volt/Hertz closed-loop control using PI-controller [19]

Control structure can be cascaded from only speed loop to add inner current loop, allowing more accurate current and torque optimization [6]. PI-control has been implemented as controller for volt/hertz system [19], [20] but alternatively Fuzzy logic control provides adopt with more straightforward design approach based from open loop data without need of motor model parameter knowledge for gain tuning [21].

### 3.2. Inverter Switching

With PWM used to switch inverter, power loss associated to voltage drop can be reduced as it decreases average power delivered to a load through fast switching control [22]. Due to its variable duty cycle, PWM is compatible with digital control applications. For motor control applications, using PWM at high switching frequency works well as inertia load are resistant to discrete effects [6]. Two most widely used in motor control are: Sinusoidal pulse width modulation (SPWM) and Space vector pulse width modulation (SVM).

SPWM is popular with scalar control [18], [19] and can be produced using intersective method, by comparing high frequency carrier signal with reference sinusoidal signal. Inverter output frequency is determined by the frequency of the reference signal. High switching frequency is desirable to facilitate harmonics filtering process. However as a drawback, inverter switching loss would also increase [23]. Techniques to eliminate unwanted harmonics include modification of carrier signal. Another drawback of SPWM includes lower output phase voltage compared to the line supply[22].

The objective of the SVM is to generate PWM load line voltages that are in average equal to reference load line voltages [22]. SVM is a digital modulating technique that treats the inverter as single unit where eight unique switching states (also referred as voltage vectors) can be driven to the unit. Eight states of the VSI consist of six active vectors ( $V_1$  to  $V_6$ ) and two null vectors ( $V_0$  and  $V_7$ ) [24]. Output voltage is created by repeatedly switching the adjacent vectors and the null vector. Reference signal is sampled regularly using encoder or resolver [25]. The popular design is alternate-reversing sequence where null vectors alternate for every sequence and the sequence reverses. Center-aligned PWM is a SVM technique that combines both features for all sectors and has been adopted commercially in most vector control applications[24].

In comparison to SPWM, SVM has proven to give superior performance in dynamic response and current distortion when implemented for motor control application and also better DC bus utilization [25]–[27] although the process of implementing SVM signal is much more complex and increased computational effort [28]. The superior performance of SVM made them more suitable to be implemented in vector control.

### 3.3. Vector Control

The scalar control is adequate when controlling the speed of compressor, fan or conveyor as the speed change is intermittent. However, dynamic applications such as electric vehicle requires motor to rapidly accelerate, reverse, stop, and start while responding to torques that may suddenly change. During such transition, the voltages and currents are no longer sinusoidal, and computer generated waveshape change instantaneously, rendering equivalent circuit-based model ineffective. Flux must be maintained both in value and orientation to instantaneously develop required torque. This type of dynamic control is called flux vector control [7]. Two most popular vector control types are field oriented control (FOC) and direct torque control (DTC). Both FOC [29] and DTC [30] control schemes have been employed in electric vehicle, obtained good dynamic performance and highly efficient over wide speed range.

#### 3.3.1. Field Oriented Control

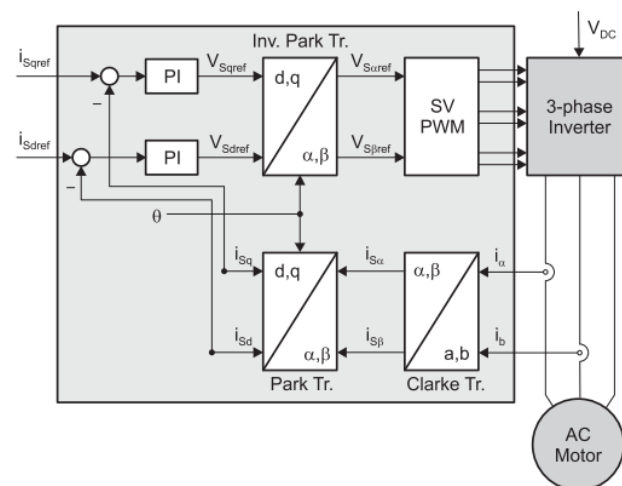


Figure 4 : Basic FOC scheme for three phase induction motor [31]

Figure 4 shows basic FOC scheme for induction motor. The concept was first introduced by F. Blaschke in 1971 [16]. Motor signals consisting stator currents and rotor position were measured. Stator currents were converted to dq-parameter using Clarke-Park transformation as feedback and were compared with reference parameter to generate error signal which was independently regulated by controller (usually PI-type). The controller sends correction signal in form of dq-parameter to be converted using Inverse Park transformation into  $\alpha\beta$ -parameter and modulated to the inverter switching gates. Rotor flux position

is needed to execute both Clarke-Park and inverse Park transformation and is usually measured from motor speed sensor. Since then several improvement on the basic system has been introduced [32], [33].

The main advantages of FOC method are high dynamic performance, switching frequency, low torque ripples and maximum fundamental component of stator current, but it suffers disadvantages such as requirement of two coordinate transformations and current controllers, and high machine parameter sensitivity [16].

### 3.3.2. Direct Torque Control

Direct Torque Control was developed by Takahashi in 1989 [34]. Figure 5 shows conventional DTC scheme for induction motor. In this scheme, stator signals were fed to flux and torque estimator, based from motor flux equations. Electromagnetic torque and stator flux would be independently compared to reference values, and their errors would be mitigated using two-level hysteresis controller for flux and three-level hysteresis controller for the torque. Control outputs, together with flux sector selection signal were fed to the switching table and the PWM output drives the inverter.

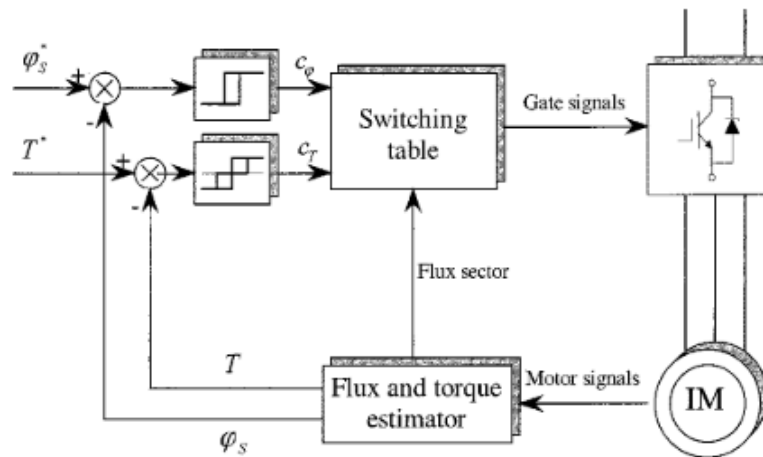


Figure 5 : Conventional DTC scheme for three phase induction motor [16]

Compared to FOC, DTC is simpler and requires less computational effort. Current controller and coordinate transformations were not required. Despite its simplicity, DTC allows a good torque control in steady-state and transient operating conditions, high dynamic response and robustness. In addition, this controller is less sensitive to the parameters detuning [16].

However, conventional DTC produces high ripple in torque due to the non-linear hysteresis controllers. This was due to the fixed width band of the controller resulting variable switching frequency. The conventional switching table also produce only one voltage space vector for the entire sampling period. Hence the motor torque may exceed the upper/lower torque limit even if the error is small [26], [35]. This worsen in digital implementation where sampling time has significant effect and the ripple may be higher than the hysteresis limits [35]. Limited selection of voltage vector also caused undesired flux weakening phenomena at low speed operation [16].

One method to circumvent the problem of non-linearity of hysteresis controller in conventional DTC was to employ variable band instead of using fixed width band. Fuzzy logic control was implemented to vary the hysteresis band based from torque error to obtain constant switching frequency. Compared to fixed band design, simulation results showed improvement of THD at stator current and reduced torque ripple [36].

Space Vector Modulation was integrated in DTC (DTC-SVM) where more voltage vectors can be utilized per sampling cycle. This allows more accurate switching according to rotor speed. With the sampling frequency maintained constant, the torque ripple at low speed can be significantly improved, produced better current harmonics [16] and minimized switching loss [26]. In another design, variable

domain adaptive fuzzy control was implemented in speed loop to generate reference torque and PI-controllers were used in place of hysteresis controllers. Compared to conventional DTC-SVM, faster transient and lower ripple of both torque and flux were achieved [37]. Instead of two active states per sampling cycle in SVM, more accurate voltage vectors can be generated using duty cycle modulation between the two states. Adaptive fuzzy logic control was implemented as modulator to select duty cycle in addition to conventional DTC scheme. Experimental results showed significant torque ripple reduction by 58% while keeping flux ripple maintained [35].

### 3.3.3. Predictive Direct Torque Control

Prediction-based DTC was proposed through estimating parameters cycles ahead and including them in comparison with reference values before feeding to independent hysteresis controllers [38]. This method modified the input prior the controllers while retaining structure of conventional DTC. Forward Euler method incorporated in discretized IM modelling managed to diminish effect of time delay caused by data processing. Compared to conventional DTC, steady state torque and flux ripples reduced by half.

Model predictive control (MPC) uses a model to predict future plant output and solves an optimization problem to select the optimal control. Unlike traditional PID controller, MPC can handle multi input multi output systems that might have interaction between input and output. MPC is also capable to preview outcomes and handle constraints, which justifies requirement of powerful and fast processor with large memory. MPC controllers have been widely used in processing industries and recently applied to healthcare, automotive and aerospace industries [39]. MPC can be classified to CS-MPC (Continuous Set MPC) and FS-MPC (Finite Set MPC), where FS-MPC has limited possible state and does not necessarily needs modulator, thus reducing computational effort [40].

MPC embedded into DTC schemes is also known as Model Predictive Torque Control (MPTC). MPTC uses discretized IM model to estimate the current, flux and torque parameter. This eliminates the need to transform to rotational frame [38] which reduces the computational effort. Stator flux and torque are then predicted to be two cycles ( $k + 2$ ) ahead. The speed is regulated at outer loop to generate torque reference and usually needs a speed sensor [41]. Reference stator was set to be fixed. The predicted parameters are then compared with reference parameter before cost function is used to evaluate minimum value as basis for selection of modulating voltage vectors.

The cost function in the MPC compares the predicted and reference values [42]. In it, the weighting factor was determined based on trade-off between the torque and flux tracking [43]. During each cycle, stator voltage and all relevant parameters such as torque and flux were evaluated for 6 different sectors. For each stator voltage vector, the cost function  $g$  is evaluated to determine the minimum value, upon which it will be selected as modulating vector to drive the inverter [44].

Figure 6 shows predictive direct torque controller with fuzzy speed controller for IM drive. In this scheme, torque reference was generated from speed error using fuzzy logic control and fed to cost function together with reference stator flux and predicted parameters. Prediction horizon for torque and stator flux was increased to two ( $k + 2$ ) to account for time delay encountered during hardware implementation [38], [41], [44].

MPTC offers lesser ripple in torque when compared with DTC. Experimental results shown significant reduction of torque and current ripple by more than 50% although flux ripple is maintained compared to DTC. Low speed operation was also improved [45]. In DTC, the hysteresis bounds were responsible to generate a switching vector, implying indirect voltage vector selection process. Whereas in MPTC the selection of the voltage vector is direct from optimization of cost function [46]. However, the optimization of cost function is dependent on torque and flux weighting factors where tuning was tedious [45]. Integration of fuzzy logic for speed control of MPTC improves the transient states and add robustness against external load [41].

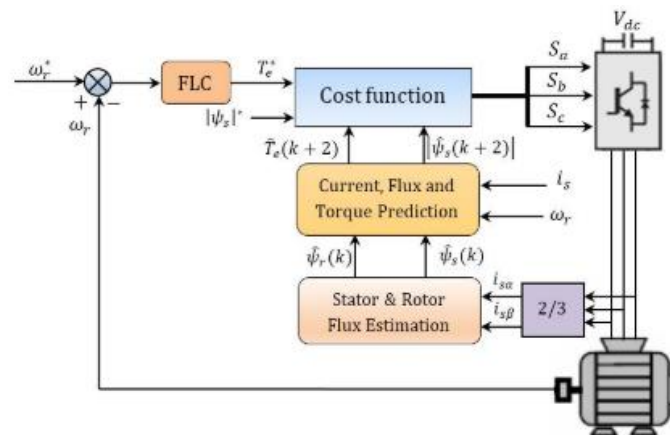


Figure 6 : MPTC with fuzzy logic scheme [41]

In Fuzzy-predictive-DTC (FPTC) scheme [47], fuzzy logic control structure is integrated to MPTC algorithm, allowing adaptive variation and dynamic rules. After cost function evaluation, fuzzy logic further process torque and flux error for tracking based on developed axis of constant torque and constant stator flux variation. The fuzzy output is then modulated using SVM for triggering. Experimental results shown significant reduction of torque and current ripple by 50% and flux ripple by 20% compared to MPTC. The design was tested to be satisfactory performance at low speed and robust to 50% variation of main parameter. However, on the downside, computational burden was increased with deployment of SVM modulator and complex fuzzy inference engine even though the design approach adopted minimal membership functions and Takagi-Sugeno inference system.

### 3.4. Sensorless Design Consideration

Most high performance control needs speed sensor measurement for accurate positioning of rotor angle in coordinate transformation, sector selection in SVM [26] or determining developed torque in speed loop [17]. Sensor coupling, inertia, torsional resonance, and the maximum sensor speed are among issues to be considered for sensor selection [6]. In electric vehicle, space and weight are among the main constraint. Hence, sensorless system might be the alternative solution.

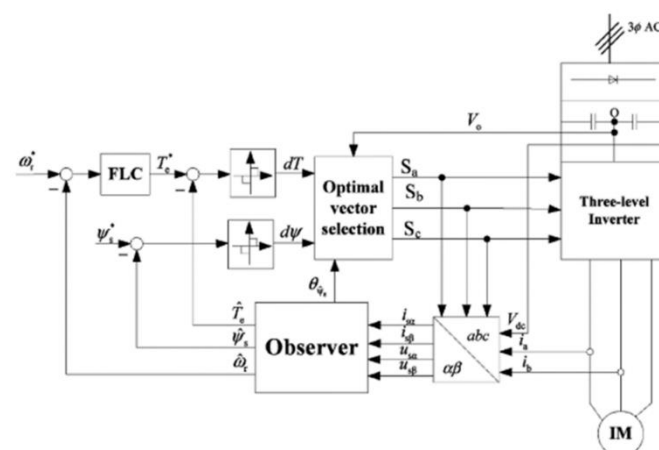


Figure 7 : Sensorless three-level DTC drive [48]

Speed adaptive flux observer was used for rotor speed measurement and was implemented on conventional DTC [48]. Figure 7 shows block diagram of sensorless DTC using speed adaptive flux observer. Estimates of electromagnetic torque and stator flux were regulated independently by hysteresis

controllers to generate corrective control action through switching table together with rotor angle for sector selection. Experimental results show that estimated and the actual speed matched at very low speed. Sliding mode observer was also used with vector control in sensorless design with better torque ripple and robust performance[49], [50].

Extended Kalman Filter (EKF) has also been proposed in sensorless design [51]. Even though EKF has good performances with noises, but the filter is unsteady with gross external disturbance and internal modeling estimation error. Setting the attenuation level to threshold value improves its robustness and lessen the error effect. [52] However, estimation error still persist even though motor dynamics control in wide speed range was effective [14].

#### 4. Performance analysis of motor control strategies

Table 1 summarizes induction motor control technologies. Only volt/hertz variable frequency drive is scalar type control while other methods were vector types. From perspective of electric vehicle application, operational features such as dynamic response, ripple performance, low speed performance, sensorless solution and cost reduction are important features to be looked into.

**Table 1.** Induction Motor Control Technology

| Literature             | Method                                                  | Findings                                                                                                                                                                                                                                                                       |
|------------------------|---------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [17], [18], [20]       | Volt/hertz variable frequency drive                     | Scalar control. Commonly used in industrial applications and driven by SPWM. Problems at low speed and not suitable with high dynamic applications.                                                                                                                            |
| [16], [32], [33]       | Conventional FOC schemes.                               | Vector control. High dynamic performance but also high computational effort due to complexity and high parameter sensitivity.                                                                                                                                                  |
| [16], [26], [36]       | DTC schemes.                                            | Simpler implementation with using switching table and hysteresis controller but at higher ripple for conventional DTC. Performance improved with integration with SVM, variable hysteresis band and additional speed control loop. However, computational time also increased. |
| [38], [41], [44], [45] | Prediction based DTC using MPC (MPTC).                  | Uses cost function as alternative to using SVM and coordinate transformation has improved the torque ripple and good low speed performance at reduced computational effort.                                                                                                    |
| [27]                   | Fuzzy-predictive torque control (FPTC)                  | Integrates fuzzy structure after cost function and output modulated using SVM. Improved dynamic rule base designed. Significant torque and flux ripple reduction of compared to MPTC. Robust and satisfactory low speed performance. Downside is high computational burden.    |
| [48]–[50]              | Observer for sensorless speed on vector control system. | Excellent actual speed matching down to very low speed for discrete SVM despite trade-off at high load with sliding mode observer provides better ripple performance.                                                                                                          |
| [14], [52]             | EKF for sensorless speed control.                       | Alternative to observer design. However internal speed estimation error persisted and susceptible to gross disturbance.                                                                                                                                                        |

In terms of dynamic response, all vector control strategy has superior performance over scalar control due to advanced induction motor modelling that maintains flux in dynamic condition. For vector control strategy, advantages of DTC over FOC are elimination of current regulators, coordinate transformations,

less sensitivity to the parameter detuning, simple implementation, high dynamic response and robustness. However, the drawbacks include high current, flux and torque ripple, variable switching frequency and lack of direct current control. Implementing SVM to substitute switching table adds more voltage vectors, generate constant switching frequency which reduces current and torque ripple by 50% to be in par with FOC. However, the problem persists at low speed operation. This was circumvented in MPTC which uses predictive algorithm and cost function to substitute SVM to further improves current and torque ripple by 50% at reduced computational burden. Low speed performance was also improved. FPTC integrates dynamic fuzzy rules after cost function and SVM. Compared to MPTC, FPTC produced 20% lower flux ripple and 50% lower current and torque ripple. However, FPTC requires high performance computing due to complex fuzzy inference engine and modulator deployment.

FPTC design may be robust and produce best ripple performance, but requires high performance computing. MPTC still produce excellent dynamic performance even at low speed with relatively higher ripple but was significantly improved over DTC and FOC design. For sensorless solution, EKF and observer has been used as speed estimator in the system. Sliding mode observer has been widely used in DTC with improved accuracy compared to EKF which suffers from estimation error and lack robustness. MPTC with its predictive features may be used together with sliding mode observer to provide sensorless control solution for electric vehicle.

## 5. Conclusion

This paper has reviewed the control technologies associated for induction motor in industrial application to electric vehicle. As prime mover in electric vehicle, expected high performance includes excellent dynamic performance, low torque and flux ripple particularly at low speed and sensorless solution for less complexity. MPTC with its predictive algorithm features may be used together with sliding mode observer to provide sensorless control for electric vehicle due to excellent dynamic performance even at low speed while producing low torque and flux ripple. The features achieved at low computational burden with relatively simpler structure bode well with low cost requirement for electric vehicle.

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