DIRECT TORQUE CONTROL TECHNIQUE IN INDUCTION MOTOR DRIVES - A REVIEW

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ABSTRACT

The aim of this paper is to review the origin and developments of direct torque control (DTC), an advanced control technique of induction motor drives yielding superior performance. The direct torque control is one of the excellent control strategies available for torque control of induction machine. It is considered as an alternative to field oriented control (FOC) technique. The DTC is characterized by the absence of PI regulators, co-ordinate transformations, current regulators and pulse width modulated signal generators. DTC also allows a good torque control in steady state and transient operating conditions. In this paper, development of DTC is discussed. The DTC based on space vector modulation (SVM) and switching table has been reviewed. With successively improving reliability and performance of digital technologies, digital control techniques have predominated over analog techniques. Digital control techniques are carried out with microcontrollers, digital signal processors due to their software flexibility and low cost which are being reviewed. Intelligent control techniques like neural networks (NN) and fuzzy logic based DTC are reviewed. Field Programmable Gate Arrays (FPGAs) are a useful platform for the implementation of high bandwidth control systems and the role of FPGA on DTC based induction motor drive is also presented.

Keywords: Direct Torque Control, Field Programmable Gate Array, Fuzzy Logic, Induction Motor, Space Vector Modulation, Neural Network

1. INTRODUCTION

The Induction Machine (IM) has been widely used in industries due to its relative cheapness, low maintenance and high reliability [1]. The control of IM variable speed drives [2], [3] often requires control of machine currents, which is achieved by using the Voltage Source Inverter (VSI). The scalar control of IM drives with inverters is widely used in low cost applications. The main advantage of v/f control is its simplicity and for this reason it has been traditionally implemented using low cost microcontrollers. For those applications, which require higher dynamic performance than v/f control, the dc motor like control of IM, referred to as Field Oriented Control (FOC) is preferred. The main issue of FOC drive is how to obtain the decoupled control of machine flux and torque [4]. An indirect form of FOC is also used in IM drives, used in high performance applications. A new concept of control, quite different from that of the FOC yielding quick response and high efficiency in IM has been proposed and discussed in [5] - [7]. The key features of this method are 1) The proposed scheme is based on limit cycle control of both flux and torque using optimum PWM output voltage; a switching table is employed for selecting the optimum inverter output voltage vectors so as to attain as fast a torque response, as

low an inverter switching frequency and as low harmonic losses as possible. 2) The efficiency optimization in the steady-state operation is also considered; it can be achieved by controlling the amplitude of the flux in accordance with the torque command. To verify the feasibility of this scheme, experimentation, simulation and comparison with field-oriented control are carried out. The results prove the excellent characteristics for torque response and efficiency, which confirm the validity of this control scheme.
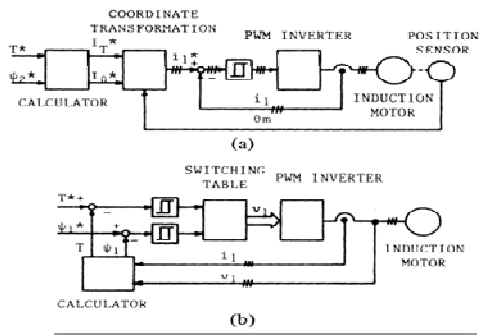

Figure 1 Torque control schemes. (a) Field-oriented control. (b) Direct torque control [6]

Figure 1(a) shows typical system configuration employing FOC. The system usually employs a position sensor to drive a rotating reference frame transformation, which generates the phase current commands for the current controlled inverter. The primary current reference i* is calculated from the flux command ψ* and the torque command T* by using an estimator. The control equation for the estimator contains motor parameters which vary with the winding temperatures and the flux saturation level of the iron core. Fig. 1 (b) shows a schematic diagram of the proposed control scheme. In the system, instantaneous values of the flux and the torque are calculated from primary variables and controlled by using an optimum switching table. Therefore, it can achieve not only the fastest torque response but also the lowest harmonic losses and acoustic noise.

In [8] the performance of the two control schemes DTC and FOC is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command. The analysis has been carried out on the basis of the results obtained by numerical simulations, where secondary effects introduced by hardware implementation are not present.

Figure 2 (a) Basic DFOC Scheme [8]

Figure 2 (b) Basic DTC Scheme [8]

Table 1 Settling Time of the Torque Response

	FOC	DTC
1200 rpm	3.8 ms	1.8 ms
600 rpm	1.8 ms	0.7 ms
100 rpm	1.7 ms	0.5 ms

The analysis has been carried out on the basis of the results obtained by numerical simulations, where secondary effects introd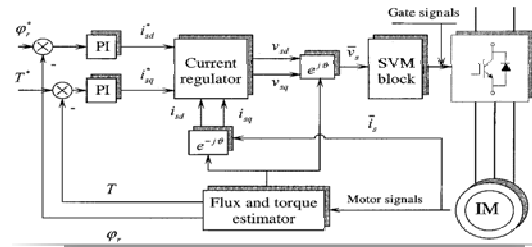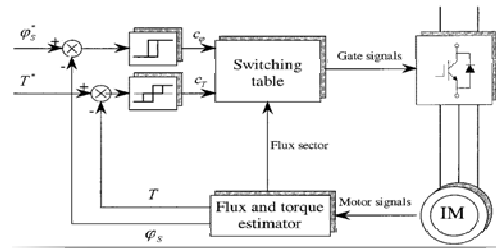uced by hardware implementation are not present. Figure 2 (a) shows the direct field oriented control (DFOC) and Figure 2 (b) shows simple DTC. The authors concluded that the whole performance of the two schemes is comparable. DTC might be preferred for high dynamic applications [9], but, on the other hand, shows higher current and torque ripple. This drawback can be partially

compensated by SVM based DTC scheme. The DTC scheme is relatively simple to implement, requiring a very small computational time when compared to FOC (Table 1).

In this review, a grouping of papers based on the control strategy is attempted and shown in Table 2. DTC based on intelligent control techniques like fuzzy logic and neural network is mainly used to reduce torque ripples. DSP and FPGA based DTC are improving the performance of drives.

Table 2 Review Based on Control Techniques

Sl.No.	Control Techniques	References
1	Fuzzy logic based DTC	[10] – [24]
2	NN based DTC	[25] - [28]
3	FPGA based DTC	[29] - [41]
4	DSP based DTC	[42] - [47]

This paper is organized as follows: Section 2 review the development of DTC and comparison of its performance with FOC. SVM based DTC is reviewed in section 3. Sections 4 and 5 reviewed the fuzzy logic and neural network based DTC respectively. FPGA and DSP based DTC are reviewed in sections 6 and 7 respectively. Finally the paper is concluded in section 8.

2. PRINCIPLES OF DTC

DTC of an induction motor has been successful because it explicitly considers the inverter stage and uses few machine parameters, while being more robust to parameter uncertainty than field-oriented control (FOC). The papers [48] and [49] present a formal and theoretical derivation of DTC based on singular perturbation and nonlinear control tools respectively. The derivation elaborates an explicit relationship between DTC performance and machine characteristics; low-leakage machines are expected to perform better under DTC. The known troublesome machine operating regimes are predicted and justified. Explicit conditions to guarantee stability are presented. Finally,

compensation strategies that extend DTC are discussed. The paper [50] presents a review of recently used direct torque and flux control (DTC) techniques for voltage inverter-fed induction and permanent- magnet synchronous motors. A variety of techniques, different in concept, are described as follows: switching-table-based hysteresis DTC, direct self control, constant switching frequency DTC with space-vector modulation (DT'C-SVM). Also, trends in the DTC-SVM techniques based on neuro-fuzzy logic controllers are presented.

Mechanical speed measurement used to be an undesired necessity for inverter-fed IM. The paper [51] presents a possible way of calculating the exact speed without mechanical devices. The control scheme is based on the analog basic version of direct self control (DSC) of inverter-fed induction machines and needs only a few additional operational amplifiers for signal processing. In [52], [53], and [54], torque control of an induction machine based on DTC strategy has been developed and a comprehensive study is presented. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package Matlab/Simulink. Several numerical simulations have been carried out in a steady state and transient operation on a speed control mode.

2.1 Problems Associated With DTC

The main problems associated with DTC are the well known torque ripples. Many papers presented different approaches to minimize the torque ripples [55] – [62]. In [55] and [61] flux linkage, electromagnetic torque are controlled directly by the selection of a switching vector from a look-up table. However, the selected vector is not always the best one since only the sector is considered where the flux linkage space vector lies without considering its accurate location. This paper presents a unified

flux and torque control method for DTC-based IM drives, where the flux and torque errors are geometrically put together to make a stator voltage vector in a deadbeat fashion. The look-up table in the DTC is replaced by a minimum-distance vector selection scheme to minimize the flux and torque ripples over a fixed sampling period. Simulation and experimental results proved that the proposed algorithm effectively reduces the flux and torque ripples. The paper [56] presents a new direct self-control (DSC) scheme for IM drives using the stator voltage third harmonic component in order to estimate the air-gap flux and the torque as well as to synchronize the supply voltage vector. Compared to previous DSC schemes the new one is independent from any motor parameter variation, specifically on stator resistance thus showing better performances at low speeds. The paper starts with a quick review on standard DSC main features pointing out the influence of stator resistance variations on the flux and torque control. The new DSC scheme is then introduced and evaluated by simulations and experimental tests on a 1.5-kW induction motor drive.

In [56] and [58] novel techniques for the DTC of an IM are proposed, which overcomes the trouble of high torque ripple afflicting the conventional DTC technique. In [57] the inverter voltage vector selected from the switching table is applied for the time interval needed by the torque to reach the upper (or the lower) limit of the band, where the time interval is calculated from a suitable modeling of the torque dynamics. By this approach, the control system emulates the operation of a torque hysteresis controller of analog type since the application time of the inverter voltage vector is dictated by the allowed torque excursion and not by the sampling period. It is shown by experimental results that the technique yields a considerable reduction of the torque ripple. In [58] a constant switching frequency torque controller is proposed to replace the conventional hysteresis-based controller. The

proposed controller is shown to be capable of reducing the torque ripple and maintaining a constant switching frequency. In [59] the proposed HPWM method is developed based on notion of stator flux ripple which can be used for a measure of ripple in the line current. Expressions for mean square flux ripple, over a sub cycle are derived for each switching sequence and this analysis together with the total harmonic distortion (THD) performance of each sequence is used to develop the HPWM method for induction motor drives. The proposed PWM method improves the performance of the drive in terms of ripple at all modulation indices. In [60] a three level SVM based DTC is proposed. A predictive torque control is proposed in [61] to reduce torque ripples. In [62] a sliding mode controller is investigated which features in very low flux and torque ripple. In order to guarantee electromagnetic torque and stator flux to track its reference signal strictly, the electromagnetic torque sliding mode variable and stator flux sliding mode variable were selected separately. Furthermore, a robust stator flux observer is designed for sliding mode direct torque controlled induction motor system. The design of state observer is based on regional pole assignment theory. The observer gain matrix is obtained by solving linear matrix inequality (LMI) using LMI Toolbox in MATLAB. Finally, the effectiveness and validity of the proposed control approach is verified by computer simulation results.

2.2 Improvements Suggested on DTC

With conventional DTC some additional modifications are performed to improve the performance of DTC. In papers referred under [63] – [84], certain advancements on DTC are discussed and experimental results are presented to indicate the gains as a result of them. Table 3 shows the references along with modifications.

In [63], a sensorless IM drive is

presented, in which the principles of sliding-mode control (SMC), DTC, and SVM are combined to ensure high-performance operation both in the steady state and under transient conditions. In particular the SMC contributes to robustness of the drive, the DTC results in a fast dynamic response, and the SVM improves the torque, flux and current steady-state waveforms by ripple reduction. The sliding-mode state observer of an IM has been proved stable and accurate. Computer simulations and experimental results presented demonstrate the robustness, accuracy, quickness, and low chattering, wide-speed-range operation of the drive.

In [64] a prediction scheme is presented to diminish both the torque and flux ripples in a DTC based IM drive.

Table 3 References Showing Improvements

Sl.No.	Ref.	Improvements
1	[83], [84]	FEM based DTC
2	[65], [66]	DTC with H-bridge inverter
3	[72]	Improved stator flux estimation with low pass filtering
4	[75]	DTC in transition region
5	[76]	Extension of DTC
6	[69]	DTC with dynamic over-modulation
7	[70]	DTC with different observers
8	[68]	Model predictive DTC
9	[67]	DTC for five phase drives with increased number of voltage vectors
10	[64]	DTC with prediction scheme
11	[82]	DTC with matrix converter
12	[81]	DTC using 12 sided polygonal voltage space vector
13	[77]	Efficiency improvement in DTC
14	[78]	DTC with multilevel inverters
15	[80]	DTC with single current sensor
16	[71]	DTC with Deadbeat controller
17	[74]	DTC with unified flux controller
18	[73]	Improved DTFC
19	[79]	DTC for vehicles
20	[63]	DTC with sliding mode controller

In a discrete implementation of the classical DTC scheme, the time delay associated with data processing results in additional torque and flux ripples. This part of the ripples can amount to a significant fraction of the overall ripple if the hysteresis bands are comparable to the maximum torque and flux variations in one sampling interval. This paper presents a prediction scheme with low computational complexity and low parameter sensitivity, both comparable to the standard DTC scheme. The papers [65], [66] and [79] present a motor drive controlled by DTC for electric vehicles (EVs) or hybrid EVs. The stator voltage vector reference is computed from the stator flux and torque errors imposed by the flux and torque controllers. This voltage reference is then generated using a hybrid cascaded H-bridge multilevel inverter, where each phase of the inverter can be implemented using a dc source, which would be available from fuel cells, batteries, or ultra capacitors. This inverter provides nearly sinusoidal voltages with very low distortion, even without filtering, using fewer switching devices.

As DTC is a variable-structure control strategy with simplicity, fast response, and tolerance to motor parameter variation, which provides direct control of stator flux and electromagnetic torque by optimally selecting the inverter states in each sampling period, it is preferred for five-phase drives in which the increased number of voltage vectors offers greater flexibility in optimizing the selection of the inverter states, thereby accomplishing more precise control of stator flux and torque [67]. Nevertheless, the large number of inverter states means that a more elaborate and complex selection criterion is needed. The following two aspects, which are not issues for three-phase

drives, are taken into account in designing switching-table-based DTC for five-phase drives. First the low-frequency harmonic currents due to the auxiliary vector plane need to be eliminated. Second, full utilization of the dc-link voltage is desired. A novel switching-table-based direct torque controller fulfilling these objectives is proposed and is combined with a speed-adaptive variable-structure observer. For medium-voltage drives, model predictive direct torque control (MPDTC) significantly reduces the switching losses and/or the harmonic distortions of the torque and stator currents, when compared to standard schemes, such as DTC or pulse width modulation which is presented in [68]. In [70], two methods of speed estimation i.e. open and closed loop observation method. It is observed that speed estimation is more reliable and more efficient with closed loop observers which are expressed in the cases of dynamic behavior of' the system. The disadvantage of this method is that, in practice, an increased amount of time is required by microcontrollers. With open loop estimators, system control for low speeds is problematic.

In [69] a dynamic over modulation strategy for fast dynamic torque control based IM is proposed. The fastest dynamic torque response with a six-step mode can be achieved in the proposed method by switching only the most optimized voltage vector that produces the largest tangential component to the circular flux locus. This paper also discusses the performance of dynamic torque control in basic DTC in order to justify on how the proposed selected voltage vector results in excellent dynamic torque performance. The main benefit of the proposed method is its simplicity, since it only requires a minor modification to the conventional DTC-hysteresis- based structure and does not require a space vector modulator. To verify the feasibility of the proposed dynamic over modulation strategy, simulation and experimentation, as well as comparison with the conventional DTC scheme, are carried out. Results showed a significant improvement in the dynamic torque response when compared to the conventional DTC hysteresis- based method.

In [71], properly formed discrete-time recursive models of a stator and rotor flux-linkage observer are presented. A model delay in the flux-linkage observer, which hindered previous work, is identified. To remove this delay, a new stationary frame current observer is developed and experimentally verified. With this new observer system, the flux linkages are properly estimated for the next sample instant, thus removing the computational delay. The improved and the delayed flux observer are evaluated in a deadbeat direct torque control algorithm. In [72] an improved stator flux estimation technique based on a voltage model with some form of low-pass (LP) filtering is presented. In voltage-model-based stator flux estimation, an LP filter is normally used instead of a pure integrator to avoid integration drift problem due to dc offset, noise, or measurement error present in the back electromotive force. In steady-state condition, the LP filter estimator will degrade the performance and efficiency of the DTC drive system since it introduced magnitude and phase errors, thus resulting in an incorrect voltage vector selection. The stator flux steady-state error between the LP filter and a pure integrator estimator technique is derived and its effect on the steady-state DTC drive performance is analyzed. A simple method is proposed to compensate for this error which results in a significant improvement in the steady-state drive performance. Simulation based on this technique is given and it is verified by experimental results. In [74], the authors introduced a unified direct-flux vector control scheme that is suitable for sinusoidal ac motor drives. The ac drives considered here are induction motor, synchronous reluctance, and synchronous permanent-magnet (PM) motor drives, including interior and surface-mounted PM types. The proposed controller operates in

stator flux coordinates: The stator flux amplitude is directly controlled by the direct voltage component, while the torque is controlled by regulating the quadrature current component. The unified direct-flux control is particularly convenient when flux weakening is required since it easily guarantees maximum torque production under current and voltage limitations.

In [75], the author investigates the operation of a direct torque controlled drive when operating under transient conditions and when operating in over modulation conditions or in the "transition region" to six-step operation. The DTC is a dead-beat control of the torque and flux magnitude. A much simpler scheme is presented which utilizes the voltage reference vector from the DTC algorithm. This scheme, although not resulting in dead-beat control, is shown to provide very satisfactory performance in over modulation. The DTC method shows great promise for light traction applications where a large quasi-constant power region is required. The scheme operates very satisfactorily in over modulation, compared with existing current regulated PWM-based schemes, due to the fact that the voltage space vectors are directly controlled. A complete experimental evaluation of the proposed scheme operating in the transition region is also given. In [76], the authors propose to extend the DTC concept. This extension concerns voltage-vector generation. Based on this, it is possible to generate any voltage vector by the space-vector modulation method and apply DTC strategy at the same time. In paper [77], a flux search controller is proposed to improve the efficiency of DTC of a six-phase induction machine. The proposed flux search controller is based on adaptive gradient descent of motor flux value with fast response and easy implementation. The search controller greatly improves efficiency by reducing core loss as well as harmonics loss. The approach not only is easy to implement and adaptive with regard to parameter variations but also requires no additional hardware for practical implementation.

In recent years, multilevel inverters are becoming increasingly popular for high-power applications due to their improved harmonic profile and increased power ratings [78]. In [80], the authors propose a low-cost single shunt current sensor IM drive. The stator flux vector and the electromagnetic torque are directly calculated from the voltage and the current derived from a single dc-link voltage sensor (simple voltage divider) and a single dc-link current sensor (simple shunt resistor). The phase currents are estimated by two dc-link current measurement processes. This algorithm does not require additional computation burden or other motor parameter knowledge. In [81], a torque control scheme, based on DTC algorithm using a 12-sided polygonal voltage space vector, is proposed for a variable speed control of an open-end IM drive. The proposed scheme utilizes the exact positions of the fundamental stator voltage vector and stator flux vector to select the optimal switching vector for fast control of torque with small variation of stator flux within the hysteresis band. In [82] DTC with matrix converter is proposed. In [83] coupled finite element method (FEM) and system simulator is used to analyze direct torque controlled frequency converter fed standard 15 kW squirrel-cage induction motor. In [84] FEM method is used to analyse the IM losses.

3. SVM BASED DTC

In papers [85], [86] and [87] authors introduced a new direct torque and flux control based on space-vector modulation (DTC-SVM) for IM sensorless drives. It is able to reduce the acoustical noise, the torque, flux, current, and speed pulsations during steady state. The DTC transient merits are preserved while better quality steady-state performance is produced in sensorless implementation for a wide speed range. The flux and torque estimator presented and an improved voltage- current model speed observer is introduced. The proposed control topologies, simulations, implementation data and test results

with DTC and DTC-SVM are given and discussed. It is concluded that the proposed control topology produces better results for steady-state operation than the classical DTC. In [88], new scheme of DTC of IM for electric vehicles is proposed and the results of an investigation into suitable torque control schemes are also presented. The electric vehicle drive consists of rewound induction motors and a three-level IGBT inverter. The schemes investigated are FOC, DTC, and DTC using SVM. The results of Matlab – Simulink simulations and a comparison between the control schemes are presented. It is found that the DTC using SVM is best for this application. In [89] two different methods of PI controllers for SVM-DTC based induction motor drives have been studied. The first one is simple method based only on symmetric optimum criterion. The second approach takes into account the full model of IM including rotor voltage equation and uses root locus method. Some simulated and experimental oscillograms that illustrate properties of the presented controller design methods are shown. Because the traditional DTC can only uses six effective voltage vectors for the dual control of torque and flux, there exists a larger torque ripple. In addition, the inverter's switching state remains unchanged in a number of sampling cycles in the control process, and hence the system switching frequency is not constant and the capacity of power devices cannot be fully utilized. In [90] and [91] authors present a new method of the SVM which is applied to the traditional DTC. The performance of control is evaluated through simulating the whole system in Simulink and the suggested SVM-based DTC controlling system is shown to be superior to other controlling strategies investigated in the literature. It also shows that the IM settles down faster when using the suggested strategy compared to other previously studied strategies.

In [92] the authors propose an algorithm for direct flux and torque controlled

three phase IM drive systems. This method is based on control of slip speed and decoupled between amplitude and angle of reference stator flux for determining required stator voltage vector. In this proposed model, integrator unit is not required to generate the reference stator flux angle for calculating required stator voltage vector; hence it eliminates the initial values problems in real time. Within the given sampling time, flux as well as torque errors are controlled by stator voltage vector which is evaluated from reference stator flux. The DTC is achieved by reference stator flux angle which is generated from instantaneous slip speed angular frequency and stator flux angular frequency. The amplitude of the reference stator flux is kept constant at rated value. This technique gives better performance in three-phase IM than conventional technique. The paper [93] describes a combination of DTC and SVM for an adjustable speed sensorless IM drive. The motor drive is supplied by a two-level SVPWM inverter. The inverter reference voltage is obtained based on input-output feedback linearization control, using the IM model in the stator - axes reference frame with stator current and flux vector components as state variables. Moreover, a robust full-order adaptive stator flux observer is designed for a speed sensorless DTC-SVM system and a new speed-adaptive law is given. By designing the observer gain matrix based on state feedback control theory, the stability and robustness of the observer systems is ensured.

3.1 Simulation Results

Figure 3 illustrates the complete proposed model of SVM based DTC drive, which consists of an induction machine model, stator flux and torque estimators, torque and flux controllers, voltage source inverter [87]. The induction machine model used for simulation is constructed using sub system with M-file based on stationary reference frame model in d-q axes.
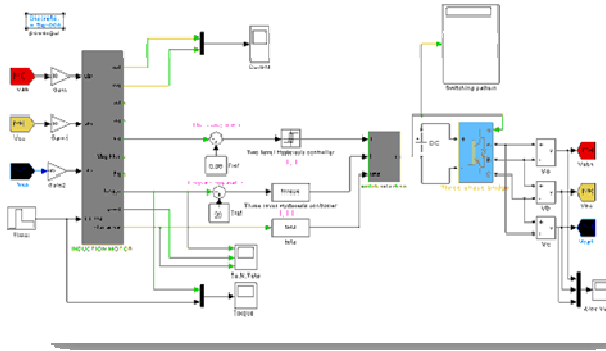
conjunction with duty ratio control.

Figure 3 Simulink Model Of Space Vector Modulation Based Direct Torque Control [87]

Simulation result of the electromagnetic torque is shown in figure 4 which proved that the torque ripples got reduced in case of SVM based DTC.
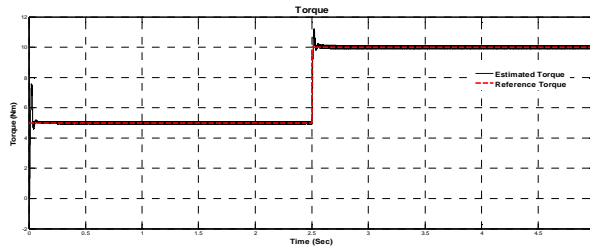

Figure 4 Simulation Results Of Electromagnetic Torque [87]

4. FUZZY LOGIC BASED DTC

Conventional DTC of IM drive has the limitations of constant duty ratio for every switching period and high torque ripples. These problems are rectified using fuzzy logic control technique as presented in [10], [11]. In [13], [15], it is presented that the implementation of fuzzy logic and artificial neural network reduced the stator flux and torque ripples.

In [14] Look-up Table based on-line tuning PI controller is proposed for outer speed control loop to achieve swift response, less overshoot and precision speed control to have wide torque-speed characteristics. A new algorithm for optimized value of stator flux based on the maximum reference value of electromagnetic torque is proposed to operate in
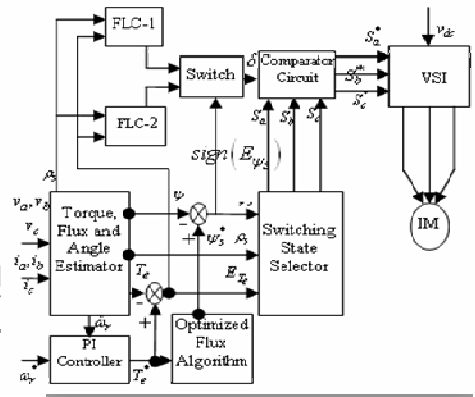

Figure 5 Schematic Diagram Of Proposed DTC With Fuzzy Logic Duty Ratio Controller [14]

Figure 5 shows the proposed DTC with duty ratio controller. To make the torque and duty ratio variations smaller, the universe of discourse of torque error and duty ratio are divided into five overlapping fuzzy sets. However, to reduce the complexity of design, the stator flux position is defined with three overlapping fuzzy sets only. The universe of discourse of all the variables, covering the whole region is expressed in per unit values. The fuzzy subsets are defined with triangular membership functions as shown in Figure 6. The linguistic labels are defined as VS = Very Small, S = Small, M = Medium and L = Large, VL – Very Large.

The simulation results shown in figure 7 clearly depict the superiority of devised method over the existing methods of DTC. In [16] the stator flux is compensated using fuzzy logic, the selection of the most suitable duty cycle value for every switching period is done, so the switching frequency of the inverter is maintained as constant. Hence the torque ripple is reduced. In [94] control of an IM using the principle of direct torque and flux control (DTFC) is proposed. This method is designed by means of fuzzy logic with three inputs and three outputs and contains 180 rules. For improvement of this method a fuzzy duty ratio controller is added. This controller prepares an optimum voltage vector (output from

fuzzy DTFC control). In this control the selected inverter switching state is applied for a portion of the switching period, defined as duty ratio, and the zero switching state is applied for the rest of the period. The duty ratio is chosen to give an average voltage vector for a change of torque with decreasing ripples. The control is verified by simulation.
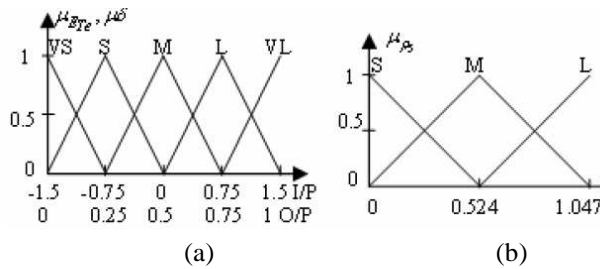

(a)   (b)

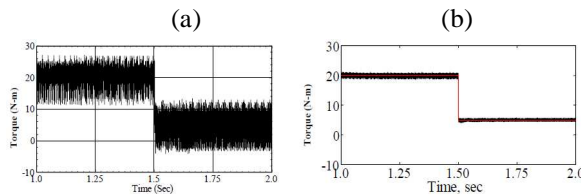*Figure 6 Membership functions for (a) torque error and duty ratio (b) stator flux position [14]*

(a)   (b)

Figure 7 Simulation results for electric torque response (a) classical DTC with reference speed of 157 rad/sec and step load [14]

In papers [17], [95] and [20], SVM based DTC is implemented using fuzzy logic. Traditional DTC of IM introduces conventional PI regulator in speed loop, it is proved that the low precision of the speed regulator debases the performance of the whole system. In [12] and [19] a fuzzy speed PI regulator was established, which applies the principles and method of fuzzy logic to adjust the proportional coefficient k_p and integral coefficient k_I of the PI regulator on-line, and finally get the system to adapt to different speed variations. The proposed method is implemented with a single board microcomputer that uses TMS320LF2407A DSP. The experimental results showed that the fuzzy speed regulator can ensure swift speed response, small

overshooting, and high steady speed precision both in high and low speed. In [18], the conventional hysteresis comparators and IP speed controller have been replaced with two Fuzzy Logic Controllers (FLC), giving rise to a Fuzzy Direct Torque and Flux Control (FDTFC), Using MATLAB/SIMULINK software environment, simulations have been made to illustrate the performances of the presented control strategy. In [22] fuzzy logic concept has been introduced into the flux model. The method of dynamic adjustment of the torque hysteresis amplitude is proposed. In this model, fuzzy variables are the speed and stator current error. Through the rationalization of fuzzy classification, the choice of voltage space vector is optimized. In [24], a simpler practically feasible FLC is designed that selects the appropriate bandwidth for the torque hysteresis controller to optimize the ripple level in the developed torque and, hence, to improve the motor speed response. Two kinds of modified DTC schemes have been proposed in [23] and both achieve high-performance sensorless control of a three-level inverter-fed motor drive. They both work over a wide speed range and overcome the limitations caused by the topology of the three-level inverter. By using appropriate intermediate vectors, the problems of neutral point balance and smooth vector switching are solved.

4.1 Simulation Results

Figure 8 shows the proposed fuzzy logic based DTC [95]. The model includes subsystems for flux and torque calculations and switching vector determinations. Interesting results are shown in figure 9. As shown in figure 9 the flux and torque pulsations are smaller in the proposed fuzzy logic based DTC compared with conventional DTC.
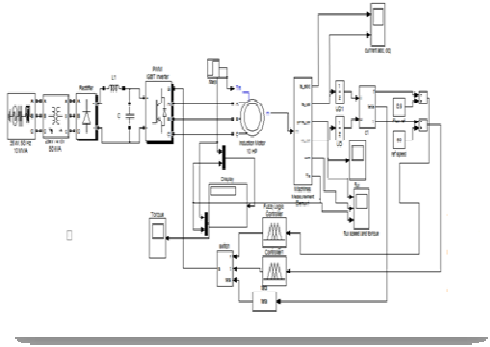
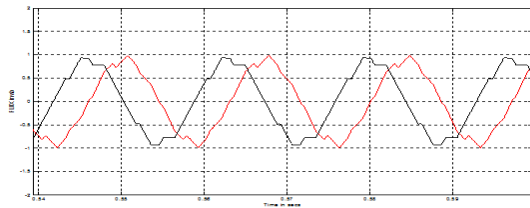*Figure 8 Simulink Model For Fuzzy Logic Based DTC [95]*

Figure 9. A The D And Q Axes Stator Fluxes In Conventional DTC [95]
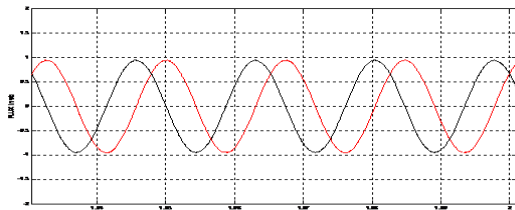

Figure 9.B The D And Q Axes Stator Fluxes In Fuzzy Logic Based DTC [95]
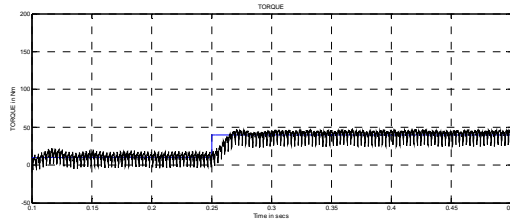

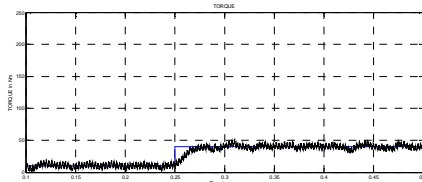*Figure 9.C The Electromagnetic Torque In Conventional DTC [95]*

Figure 9. D The Electromagnetic Torque In Fuzzy Logic Based DTC [95]

5. NN BASED DTC

The paper [25] presents simple structured neural networks for flux position estimation, sector selection and stator voltage vector selection for induction motors using DTC method. The Levenberg-Marquardt back-propagation technique has been used to train the neural network. The simple structure network facilitates a short training and processing times. The conventional flux position estimator, sector selector and stator voltage vector selector based DTC scheme compared with the proposed scheme and the results are validated through simulation. In [27] the concept and implementation of a new simple direct-torque neuro-fuzzy control (DTNFC) scheme for pulse width-modulation-inverter-fed induction motor drive is presented. An adaptive neuro-fuzzy inference system is applied to achieve high-performance decoupled flux and torque control. The well-known disadvantages of' the DTC scheme are

• variable switching frequency;
• violence of polarity consistency rules;
• current and torque distortion caused by sector

 changes;
• start and low-speed operation problems;
• high sampling frequency needed for digital
 implementation of hysteresis comparators.

All the above difficulties can be eliminated when, instead of the selection table, a voltage modulator is applied.
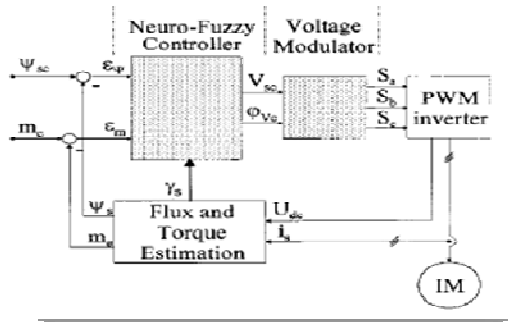
Figure 10 Proposed Scheme With Neuro-Fuzzy Controller And Voltage Modulator [27]
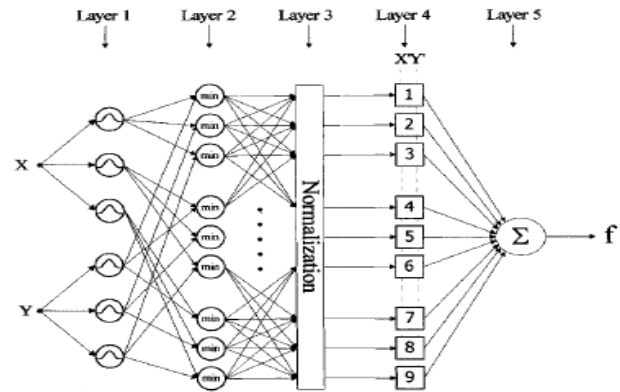

Figure 11 Two-input NF controller structure [27]

In this paper, a new controller based on an adaptive NF inference system (ANFIS) for voltage space-vector generation is proposed. This controller combines fuzzy logic and artificial neural networks for decoupled flux and torque control. Figure 10 shows the proposed NF controller with voltage modulator and figure 11 shows two input NF controller. Figure 12 shows the experimental results.

The presented DTNFC scheme has the following features and advantages:

- only one controller;
- simple tuning procedure;
- constant switching frequency and unipolar motor voltage
- torque and current harmonics mainly dependent on sampling time;
- no current and torque distortion caused by sector changes (there are no sectors borders);
- fast torque and flux response;
- no problems during low-speed operation:
- lower sampling time;
- possible online tuning;

In [28] apart from six sector look up table used for classical DTC, a modified look up table, which also use six sectors but with different zones and a twelve sector table are presented. This paper also presents the application of neural networks to control induction machines with DTC.

NN is used to emulate the state selector of the DTC. In this paper Levenberg-Marquardt algorithm is used to train the neural network. In [26] author first model the DTC of Inv-IM as a hybrid system (HS). Then, they abstract the continuous dynamics of the HS in terms of discrete events to obtain a discrete event model of the HS.
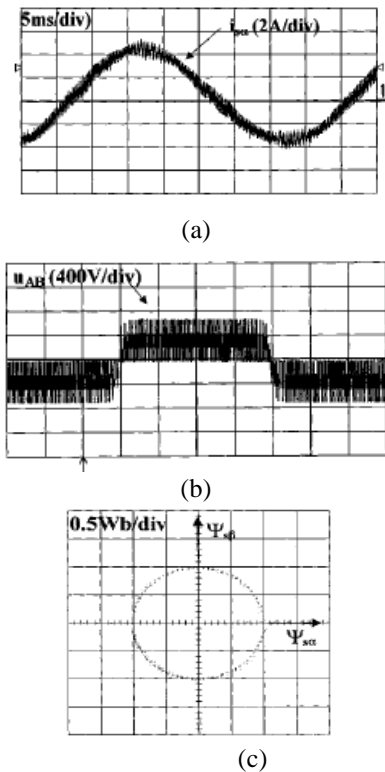

(a)

(b)

(c)

Figure 12 Experimental results for the steady state-operation for the tuned DTNFC system;

(a) Stator current (b) Line to line voltage (c) Stator flux trajectory [27]

6. FPGA BASED DTC

Modern AC drives require a fast digital realization of many mathematical operations concerning control and estimator's algorithms, which are time consuming. Therefore developing of custom-built digital interfaces as well as digital data processing blocks and sometimes even integration of ADC converters into single integrated circuit is necessary. Due to the fact that developing an ASIC chip is expensive and laborious, the FPGA based solution should be used on the design stage of the algorithm. In [36], the application of FPGA in DTC of IM drive is presented. In [30], the DTC was implemented in FPGA using fixed point arithmetic with a variable word-size approach. This is proposed as an alternative to 16 or 32-bit choices used before. A separation of the algorithm in functional blocks is used to simplify validation task which was accomplished in comparison with MATLAB results. Following a tendency in the research area, the algorithm proposed is implemented in unique FPGA device, which allows for a faster validation and simplifies the control structure. To ensure a proper voltage vector selection by the DTC controller, the estimation of stator flux must be accurate. The calculation of the electromagnetic torque too, depends on the accuracy of stator flux estimation. Most of the stator flux calculation is based on voltage model, current model or the combination of both models. These models require a precise calculation to accurately estimate the flux.

In [33], an arithmetic approach of DTC strategy using complex number and floating point representation is implemented using FPGA. The motor / inverter dynamics is executed in Matlab / Simulink. The Xilinx software performs the speed control and the DTC procedure which is written in VHDL (Very high speed integrated circuit hardware Description Language). Simulation results of this high performance drive system on 1/4 hp standard induction motor are as expected and agree with the theoretical work. This work shows the simulation of the DTC control technique using Matlab / Simulink with Xilinx/ ModelSim program simultaneously, allowing a global co-simulation of the motor dynamics and the DTC strategy coded in VHDL. The inverter drive and the induction motor were implemented in a Matlab/ Simulink environment as in figure 13. The DTC control strategy was implemented in VHDL language using Xilinx program. DTC strategy was executed exclusively in VHDL, using complex number calculation with floating point representation. For a fixed point representation all the quantities (data and constants) are represented by integers in a fixed range. This means that each must be converted to fit within this range. This must be done without decreasing accuracy. Complex number and floating point representation in DTC scheme gives higher computational accuracy than the fixed point representation.
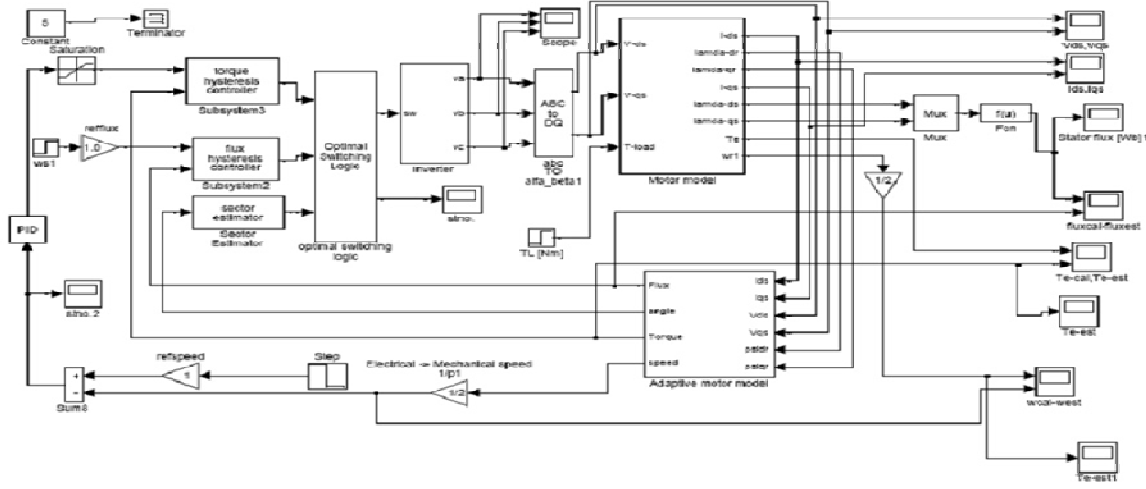
Figure 13 Matlab/Simulink diagram representation of the DTC induction motor drive system [33]

In this representation, all the variables and every mathematical operation are directly described. The use of complex number calculation with floating point representation is new proposal of this work with regard to similar study.

The paper [31] introduces a new digital logic design, which combines the DSP and FPGA to implement the conventional DTC of induction machine. The DSP will be used for floating point calculation whereas the FPGA main task is to implement the hysteresis-based controller. The emphasis is on FPGA digital logic design. The simulation and experimental results are presented and summarized. The paper [40] presents a simple approach to design and implementation of DTC of three phase squirrel cage induction motor using Matlab/Simulink and FPGA software. To maintain the simplicity of DTC while at the same time improving the performance two simple new techniques i.e. constant switching frequency and stator flux estimation are proposed. To maintain a constant switching a simple torque control is introduced to replace the three level hysteresis comparators.

The magnitude and phase error associated with stator flux estimation based on voltage model is compensated by using simple compensator which is based on steady state

operation. In [29] the author proposed a pair of torque and flux controllers to replace the hysteresis based controllers as in figure 14. The design of these controllers is fully discussed and a set of numerical values of the parameters for the proposed controllers is given. The simulation of the proposed controllers applied to the DTC drive is presented and simulation results are then verified by experimental results.
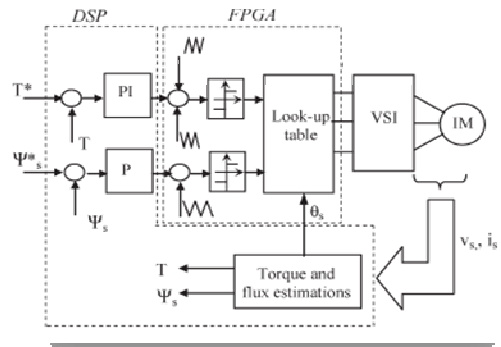

Figure 14 Implementation of proposed controllers using DSP and FPGA [29]

The hardware implementation is mainly constructed by using DSP TMS320C31 and Altera field-programmable gate array devices. The results prove that a significant torque and stator flux ripples reduction is achieved. Likewise,

the switching frequency is fixed at 10.4 kHz and a more sinusoidal phase current is obtained. The paper [34] describes a combination of DTC and SVM for an adjustable speed sensorless IM drive. The motor drive is supplied by a two level FPGA-based SVPWM inverter. The inverter reference voltage is obtained based on input-output feedback linearization control, using the IM model in the stator d-q axes reference frame with stator current and flux vectors components as state variables. In addition, a conventional PI speed controller is employed to generate the reference torque signal. Moreover, a novel Lyapunov based nonlinear stator flux observer is developed which provides simultaneous estimation of the stator flux, rotor speed, and rotor and stator resistances. Finally, the effectiveness and validity of the proposed control approach is verified by computer simulation and experimental results.

In [39], [38] and [35] the FPGA is applied to the whole speed sensorless DTC control structure. This application contains decomposed DTC and the speed observer algorithms, with the supervised speed controller. The DTC algorithm was decomposed as follows:
-
- data acquisition,
- algebraic coordinate transformations of measured stator phase currents and calculated stator voltages from phase variables ABC to stationary reference frame values α-β
- estimation of the stator flux vector coordinates.
- electromagnetic torque estimation,
- determination of the stator flux's amplitude and position (using CORDIC) for the sector N determination,
- sector determination,
- comparators' states determination,
-determination of the appropriate set of the inverters switch on states.

The observer algorithm was decomposed into the following tasks:
- estimation of the stator current coordinate in α axis,
-estimation of the stator current coordinate in β axis,
- estimation of the rotor flux coordinate in α axis.
- estimation of the rotor flux coordinate in β axis.
- adaptation mechanism and speed estimation.

The stator flux coordinates $\psi s\alpha$, $\psi s\beta$, are transformed to polar coordinates (ψs, γs), using the CORDIC scheme. Few issues concerning the implementation of IM drive control structures in FPGA are discussed. The use of CORDIC algorithm for some mathematical operations in the DTC method is described. Experimental test results of this drive control structure realized in FPGA are demonstrated. The example of the sinusoidal signals transients and their magnitude as well as rotation angle, determined using the CORDIC algorithm are presented in the figure15a, while the calculated stator and rotor flux hodographs are shown in figure 15b, c.

Simulations are carried out when System Generator (SG) toolbox working in the MATLAB/ SIMULINK environment. The results are presented and discussed to evaluate the DTC operating under considered faults.

In [37], authors present a FPGA-based implementation of Direct Torque and Stator Flux Control (DTSFC) and Direct Torque and Rotor Flux Control (DTRFC) with and without use of SVM for induction motor drives. Simulations are carried out when System Generator (SG) toolbox working in the MATLAB/ SIMULINK environment.
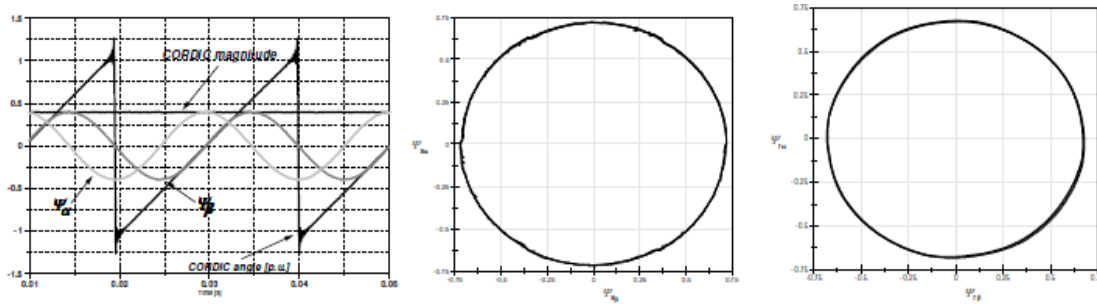
Figure 15 An Example Of The Sinusoidal Signal Magnitude And Angle Transients, Determined Using CORDIC In Translation Mode (A) Holographs Of The Stator (B) And Rotor (C) Fluxes [35]

The results are presented and discussed to evaluate the DTC operating under considered faults.

In [37], authors present a FPGA-based implementation of Direct Torque and Stator Flux Control (DTSFC) and Direct Torque and Rotor Flux Control (DTRFC) with and without use of SVM for induction motor drives. Indeed, due to their similar structures but also their differences, this set of algorithms is a good example to show the effectiveness of a FPGA-based modular approach to implement sensorless control induction motor drives. Therefore, the chosen solution is based on a custom hardware architecture designed by assembling a set of building blocks. These blocks are tested and organized in a library of Intellectual Property (IP) modules for easy re-use. Each block is geared toward specific algorithm function (Flux estimator, Hysteresis controller...). Besides, a special attention is given to the algorithm refinement which allows finding the optimum fixed-point data word length. Finally experimental results are shown which validate the proposed approach. In [32] a microcomputer-based direct primary flux and torque control system for the three-phase induction motor is presented, showing that the instantaneous primary flux of the induction motor can be calculated by means of computer software. The control algorithm can be implemented on line with an 1 K-ROM memory. The controller, therefore, can be quite compact, and both the hardware and software implementations are easy to achieve. A full digital controller with a 16-b microcomputer is developed. The experimental results are presented and agree with the theory.

Efficiency optimization of IM drives is a major subject based on these drives extensive use in the industry. Among the different proposed methods, a model based approach (MBA) seems to be the fast one [41]. However, this method needs the motor parameters that must be correctly identified. On the other hand, a search-based approach (SBA) is a parameter-independent method but needs a greater convergence time. In this paper, a novel model-based loss-minimization approach is presented, which is combined with a back stepping DTC of the IM drive. An improved search-based method for efficiency optimization is also introduced. The proposed controller is realized in the stationary reference frame and has a fast-tracking capability of rotor flux and electromagnetic torque. Moreover, a sliding-mode rotor-flux observer is introduced, which is employed for simultaneous determination of rotor-flux space vector, rotor speed and rotor time constant. The proposed control idea is experimentally implemented in real time using a FPGA board synchronized with a personal computer. Simulation and experimental results are finally presented to verify the effectiveness of the method proposed.

6.1 Simulation Results

The SVM based DTC was developed

and simulated using ModelSim 6.3 and the simulation results are shown in figure 16.
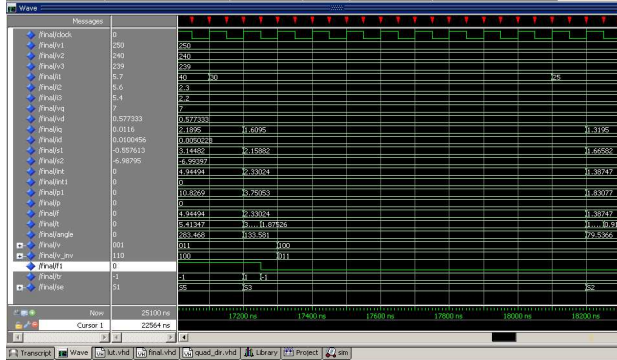

Figure 16. Simulation results showing the sector selection S2 for an angle 79.5 (60 > α > 120)

The simulation result also showed the three phase (abc) to two phase (dq) transformation, stator flux and torque estimations and proper sector selections from table 4 based on SVM technique.

Table 4 Switching Table of Inverter Voltage Vectors

Ψ_{serr}	T_{eerr}	α(1) sect 1	α(2) sect 2	α(3) sect 3	α(4) sect 4	α(5) sect 5	α(6) sect 6
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

7. DSP BASED DTC

In [45] two different strategies (1) Conventional DTC and (2) Space vector PWM based DTC are tested and implemented. The entire simulation is performed in real time using TMS320LF2407 digital signal processor. The dynamic machine model with 5 state variables is solved in real time in order to determine the state variables and hence various output quantities. Using the same controller and software used in HIL simulation and with additional signal conditioning interface circuitry, the results obtained from real time simulation are experimentally validated on a 1.5-kW induction motor drive. A new tool known as "automatic code generation" is introduced, which is capable of generating assembly language code for real time simulation of electric drives. The results of real time simulation and those obtained from a laboratory prototype are presented.

Speed control of DTC induction motor drives depends on effectively establishing the stator flux. However, it becomes difficult when the motor operates in the low speed region, because the voltage drop on the stator resistance is comparable with the input stator voltage. Therefore, the study in [43] proposes an easy but effective way to compensate the voltage drop on the stator resistance so that the stator flux can be constructed without identifying the stator resistance as done by most authors. As a result, motor torque is constructed due to the effective stator flux compensation, which makes the DTC applicable to induction motor drives in the low speed region. Moreover, a fixed-point digital signal processor (DSP)-based hardware experimental system is built to demonstrate the effectiveness of the proposed control method. The paper [46] describes a control scheme for direct torque and flux control of induction machines based on the stator flux field-orientation method. With the proposed predictive control scheme, an inverter duty cycle has directly calculated each fixed switching period based on the torque and flux errors, the transient reactance of the machine, and an estimated value of the voltage behind the transient reactance. The paper describes a method by which a voltage space vector can be calculated in order to control the torque and flux directly in a deadbeat fashion. The inverter duty cycle can then be calculated using the space vector PWM technique. With this scheme, the requirement of a separate current regulator and PI control of the flux, torque, and/or current error is eliminated, thereby improving transient performance. The implementation of the control scheme using DSP-based hardware is described with complete experimental results given. In [42], the authors proposed an algorithm which provides decoupled

control of the torque and flux with constant inverter switching frequency and a minimum torque and flux ripple. Compared to the other DTC methods, this algorithm is much simpler and has less mathematical operations, and can be implemented on most existing digital drive controllers.
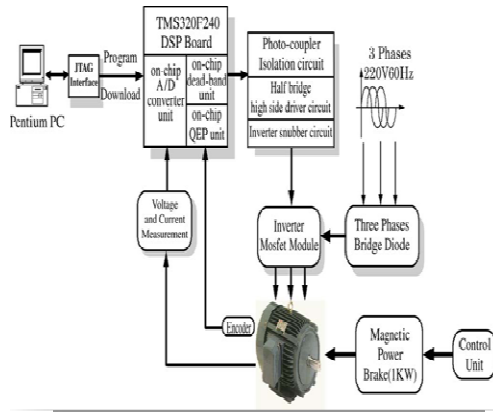

Figure 17 Experimental Setup Of The Proposed Method [47]

Algorithm is based on imposing the flux vector spatial orientation and rotation speed, which defines the unique solution for reference stator voltage. The implementation of the control scheme using DSP – based hardware is described, with complete experimental evidence and the straightforward implementation instructions.

The paper [47] proposed a simple but effective method to reduce the torque ripple for DTC of IM drives. The proposed DTC provides a global minimum torque ripple, which satisfies the root-mean-square (rms) criteria of torque ripple. Such a global minimum torque ripple DTC has not been derived before. The proposed global minimum torque ripple DTC is a two-step design. The first step drives the torque error to zero at the end of the control period. Then, the second step reduces the torque bias and rms ripple by modifying the asymmetry switching patterns of the applied voltage vectors of the first step into symmetry ones. Theoretical analysis is provided to show that the torque ripple of the proposed DTC is a global minimum rms ripple. Furthermore, to verify the effectiveness of this study, a DSP-based experimental induction motor DTC drive system is built and shown in figure17 and figure 18. In [44] a novel scheme for the direct torque control (DTC) of an induction motor (IM) is proposed, which uses a single sensor of current inserted in the inverter dc link. The rationale behind the proposal is to develop a low-cost but high performance IM drive. The scheme exploits a simple and robust algorithm to reconstruct the stator currents needed to estimate the motor flux and torque.

The algorithm operates in two stages: first, it predicts the stator currents from a model of the motor and then adjusts the prediction on the basis of the sensed dc-link current. Experimental results are given to demonstrate the ability of the scheme in reproducing the performance of a traditional DTC IM drive.
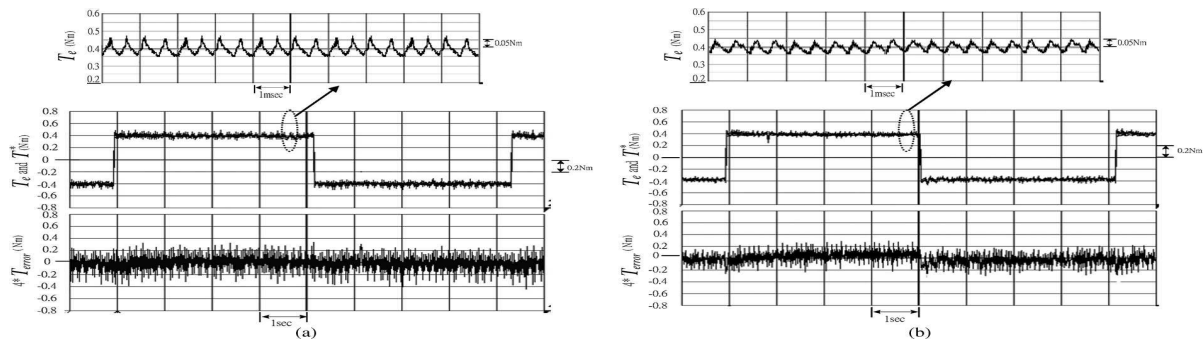

Fig. 18 Experimental Torque Responses. (A) Minimum Ripple DTC, (B) Proposed Global Minimum DTC [47]

8. CONCLUSION

This paper reviewed the origin and development of advanced control technique called direct torque control and its superior performance on induction motor drive. First the basic principle of DTC and FOC are carefully reviewed and compared. Then the problems associated with DTC and the proposed solutions are reviewed. Certain modifications on DTC to get improved performance are also discussed.

Further, implementation of intelligent control techniques such as fuzzy logic and neural networks on DTC are reviewed and the improvements are systematically analyzed. It has been concluded that the implementation of intelligent techniques reduced the stator flux and torque ripples and therefore the dynamic performance of the drives are improved. Then the implementation of DTC using FPGA is reviewed and results are discussed. It has been proved that hardware realization can be done easily using FPGA, but there exists a problem in estimating stator flux accurately due to fixed point representation. This problem could be solved if the algorithm is implemented using digital signal processors as presented.

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