A Survey of Direct Torque Control Schemes for Permanent Magnet Synchronous Motor Drives

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***Abstract*--Direct torque control (DTC) schemes have drawn strong interest recently for motor drives because of their advantages such as simplicity, good dynamic performance and insensitivity to motor parameters. Numerous attempts have been carried out to improve the basic DTC scheme mainly focusing on power electronics, flux and torque observers and DTC controllers. Many new schemes have been successfully developed and applied for not only induction motors but also permanent magnet synchronous motors. This paper aims to review these DTC schemes and their performances in motor drives with a special focus on the controller design methods.**

***Index Terms*—artificial neural network, direct torque control, permanent magnet synchronous motor, pulse width modulation, sensorless control, space vector modulation.**

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have found wide applications due to their high power density (compactness), high efficiency, ease of control, high torque-to-inertia ratio, and high reliability. A very widely used drive strategy for PMSMs is the field oriented control (FOC), which was proposed by Blaschke in 1971 for induction motors (IMs) [1]. However, the FOC scheme is quite complex due to reference frame transformation and it is highly dependent upon the motor parameters and mechanical shaft speed. To mitigate these problems, a new control strategy for the torque control of induction motor was developed by Takahashi as direct torque control (DTC) [2] and by Depenbrock as direct self control (DSC) [3]. The basic idea of DTC for induction motor is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque.

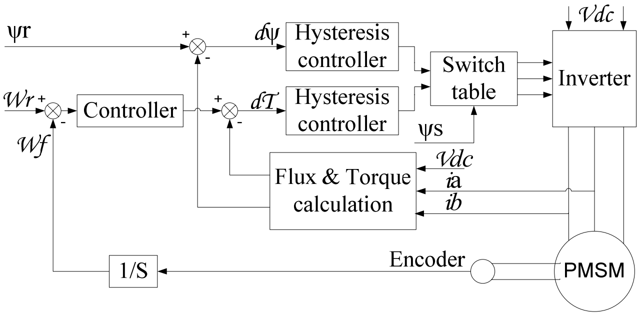

Fig. 1. Basic DTC System Diagram

It has been proven that the DTC scheme for induction motors could be modified for PMSM drive. Fig. 1 shows a typical structure of the PMSM DTC system. Since it does not require any current regulator, coordinate transformation and PWM signal generator, the DTC scheme has the advantages of simplicity, good dynamic performance, and insensitivity to motor parameters except the stator winding resistance.

Compared with the FOC, the major drawback of the DTC is the large ripples of torque and flux. As shown in Fig. 1, the switching state of the inverter is updated only once in every sampling interval. The inverter keeps the same state until the output of the hysteresis controller changes state, resulting in relatively large torque and flux ripples. Another unwanted feature is the nonconstant inverter switching frequency, which changes with the rotor speed, load torque and bandwidth of the two hysteresis controllers. In the past few years, many attempts were carried out to solve these problems, mostly on improving the hysteresis controllers or replacing them by some other types of schemes, but only limited success was achieved [4].

II. TYPICAL DTC SCHEMES FOR PMSM

In a basic DTC system as shown in Fig. 1, the voltage vector is selected among the ones deliverable by the inverter feeding the motor with the help of hysteresis controllers. This gives the drives a very fast torque response, but also causes torque ripple and varying switching frequency of inverter.

Attempts to obtain more deliverable voltage vectors by subdividing the voltage sectors have been carried out for both IM [5] and PMSM [6]. However, the torque ripple reduction was not impressive due to the transition between different sectors.

A. SVM for DTC

The concept of space vector modulation (SVM) was first introduced into DTC for IMs in 1991 by Habetler [7]. The basic idea of SVM is to adjust the flux speed by inserting zero voltage vectors to control the electromagnetic torque generated by the IM. The selection rule is based on the error vector between the expected flux linkage vector and the estimated flux linkage vector as shown in Fig. 2.

By offering accurate space voltage vectors using the SVM method, the problems of large torque and flux linkage pulsations and variable switching frequency can be solved effectively with the same hardware topology as that in the conventional DTC. This method was developed quickly in the following years. It was soon applied to PMSM [8]. The difference among various SVM DTC methods depends on the production of the reference voltage vector and the specified implementation of SVM.

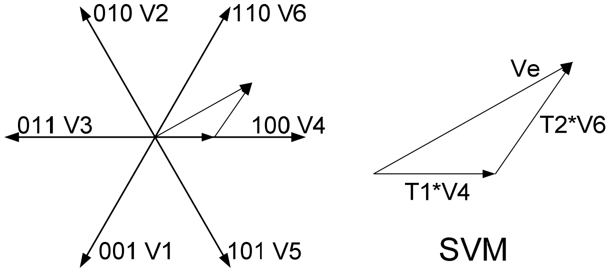

Fig. 2. Selection of Vectors by SVM

Due to the hysteresis control, the sampling frequency of an inverter with SVM in DTC must be much higher than that with FOC. It is therefore of interest to determine the switching frequency of the inverter for DTC, accounting for the fact that it varies with the operating point. In [9] the influence of the width of the hysteresis bands of the controllers on the acoustic noise radiated from IM was examined, concluding that DTC behaves similar to the random PWM technique. Paper [10] demonstrated that the inverter switching frequency is limited, even by zeroing the band of the hysteresis controllers, because of the discrete-time implementation of the control and the machine dynamics. Hence, the usage of a dithering signal was proposed to increase the switching frequency. In [11] the relationship between the inverter switching frequency and the width of the hysteresis bands of the controllers was studied in detail, together with the impact of motor parameters and speed.

It is also easy to fix the switching frequency of inverter by using SVM, and thus, zero voltage space vectors are used in every sector which is different from conventional DTC scheme based on switching table. In [12], an investigation was made about the effect of the zero voltage space vectors in the DTC system of PMSM and it was proved that the use of zero vectors can improve the performance of the system. Then one zero vector and two non-zero vectors were used in every sector for reducing the torque ripple in [13].

In recent years, some researchers tried to modify the SVM method based on novel power electronic techniques in order to not only achieve better performance but also improve power efficiency of the control system. In [14] hybrid space vector pulse width modulation (HSVPWM) techniques were developed for reduction of current ripple and switching loss. In [15], DTC was developed based on the five zones HSVPWM to reduce the ripples in torque and flux. In 2006, Brahmananda introduced a seven zones HSVPWM method into DTC [16]. To reduce the computational burden involved in continuous SVPWM, a novel voltage modulation technique was proposed in [17] using the concept of effective time. To avoid the requirement of reference voltage vector, sector identification and angle determination, the effective time was determined using the concept of imaginary switching times in [18] and then this concept was used for different switching sequences. However, it required relatively complex calculation of the stator voltage equations given in quadratic forms in the stationary reference frame.

B. Discrete SVM for DTC

To reduce the switching frequency, algorithms based on discrete space vector modulation (DSVM) technique were developed, using prefixed time intervals within a cycle period [19]. In this way a higher number of voltage space vectors can be synthesised compared to those used in the basic DTC technique. The increased number of voltage vectors allows the definition of more accurate switching tables in which the selection of voltage vectors is made according to the rotor speed, the flux error and the torque error.

As shown in Fig. 3, three equal time intervals are used in one cycle period. In each sampling period the voltage vector is selected once only, as in the basic DTC scheme. The advantage of using the DSVM technique is that one can choose among 19 voltage vectors instead of 5 of the basic DTC. On the other hand, at different speed ranges, the same vectors produce torque variations with quite different absolute values. This behaviour determines different torque ripple at low and high speeds. In the reported DSVM scheme, a set of new switching tables were established with the help of the multi-level torque hysteresis comparator and also considering the rotor speed range [19].

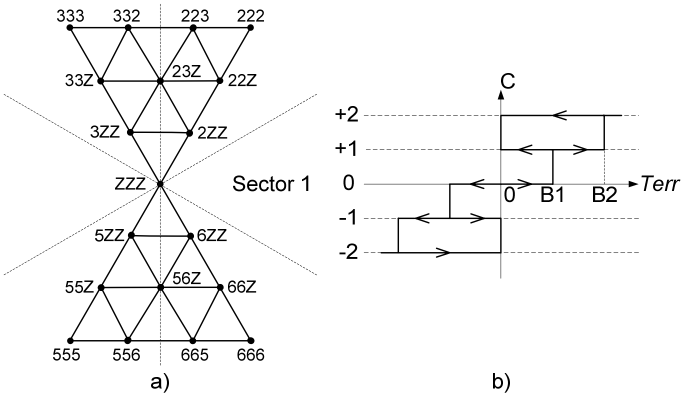

Fig. 3. (a) Voltage Vectors Obtained by Using DSVM (b) Five-level Torque Hysteresis Comparator

C. Discontinuous PWM for DTC

Several discontinuous PWM (DPWM) methods have been reported focusing on the power electronic techniques. DPWM methods use the discontinuous type of zero sequence signals. During each sampling period, one phase ceases the modulation and the associated phase is clamped to the positive DC bus or negative DC bus. Hence, the switching losses of the associated inverter leg are eliminated. The performance of the PWM methods depends upon the modulation index. In the lower modulation range, the continuous PWM (CPWM) methods are superior to DPWM methods, while in the higher modulation range, the DPWM methods are superior to CPWM methods [20]. As to the overall operating modulation indices, CPWM method has higher switching losses than DPWM methods.

An attempt toward unifying all discovered DPWM methods has led to the development of a generalised DPWM algorithm. Utilising the generalised phase shift in the DPWM methods, a carrier based PWM scheme, known as generalised discontinuous PWM (GDPWM) was proposed in [20].

A GDPWM algorithm was proposed for sensorless DTC induction motor drive by Reddy [21]. The conventional space vector PWM algorithm employs equal division of zero voltage vector times within a sampling period. A space vector based GDPWM algorithm is set forth using the freedom of zero state time division that results in different DPWM schemes. As the bus-clamped sequences are being used, the switching losses of the inverter can be reduced. Almost all these new techniques on PWM operate with a fuzzy or sliding-mode controller to handle uncertainties caused by parameter variation and load disturbance, but they have never been discussed under PMSM.

III. MODERN CONTROL THEORY BASED CONTROLLER

In the past decades, modern control theories were widely used in power and dynamic control systems. Many new DTC controllers were realised by combining traditional DTC schemes with modern control methods such as fuzzy logic control, sliding mode and artificial neural network (ANN).

A. Fuzzy DTC Controller

Fuzzy DTC (FDTC) was first introduced by Mir in 1994 [22], in which an FDTC controller was used to replace the two hysteresis controllers and the switching table to select the space voltage vector in the conventional IM DTC system. The inputs of the fuzzy controller are the errors of torque and flux linkage amplitude, and the angular position of the stator flux linkage. Each sector of 60 degrees is fuzzified into two subsets, and there is one table of fuzzy rules in each sector of the subsets, resulting in a large amount of fuzzy rules in the fuzzy controllers.

In 2004, FDTC was applied for PMSM by Dan [23]. The errors of the torque, stator flux linkage and flux linkage angular position of the PMSM are fuzzified into several fuzzy subsets in order to select a suitable space voltage vector to obtain fast torque response and to smooth the torque and flux linkage ripples simultaneously. The stator flux linkage vector angle is also mapped to one sector of 60 degrees, based on the symmetry of the control rules for each 60 degrees flux linkage angular sector, so that the torque response performance can be improved because of the minimisation of the number of fuzzy reasoning rules and hence the reasoning time.

In a DTC controller, fuzzy logic method is usually used to obtain more available subdivided vectors to minimise the torque and flux ripples. There should be a compromise between the performance and calculation cost of the fuzzy rules.

B. Sliding Mode and Variable Structure Controller

Sliding mode (SM) is a key concept of the variable structure control (VSC), a discontinuous control strategy well suited for nonlinear dynamic systems with uncertainties. The control is robust and fast, but the controlled quantity tends to exhibit undesirable chattering. DTC for inverter-fed AC drives, in which consecutive states of the inverter are selected according to flux and torque control errors, can be considered as a special case of VSC. Indeed, advantage has been derived from the variable structure nature of the inverter. Irregular chattering in the steady state is typical for the controlled flux and torque.

Sliding mode control ideas have been investigated for the SVM-DTC of induction motors, characterised by the fact that enforcing a sliding mode leads to low sensitivity with respect to a class of disturbances and plant parameter variations. In [24], for torque and stator flux control, some variable structure control methods were introduced into the frame of PI control. The fast dynamic response of classic DTC was entirely preserved, while the steady-state behaviour was significantly improved. However, the technique did not remove the disadvantages of the PI controller, such as long adjusting time and large overshoot. In [25], a sliding mode technique was adopted to realise torque and rotor flux control. If the estimated rotor flux is accurate, the control scheme achieves good transient and steady-state performance. However, it is well known that the rotor flux estimation is likely to be affected not only by the electrical parameters, but also by the mechanical parameters. Therefore the technique is hard to achieve good performance in real applications.

In [26], Ahmad attempted to synthesise the direct torque and rotor flux control strategies (DTRFC) by using the sliding-mode theory. The choice of the sliding-mode theory has been motivated by the presence of switches in the voltage source inverter (VSI). Changes in the state of the switches cause the variation in the topology of the controlled system. Two cases of VSI control were analysed: a direct control (hysteresis VSI control) using a switching table, and an indirect control by means of SVM. Finally, the two methods of VSI control were associated together in a new strategy, which is called dynamic re-configuration of VSI control algorithms. This association yields an excellent dynamic performance at transient state as a result of VSI direct control method and low chattering at steady state due to the VSI indirect control strategy.

C. ANN Based DTC Schemes

The neural network is well known for its learning ability and approximation to any arbitrary continuous function. Neural networks have recently shown good promise for application in power electronics and motion control system. It has been stated in the literatures that ANN can be applied to DTC controller design, parameter identification and state estimation of motor control systems.

In [27], an observational method of the stator flux linkage and electromagnetic torque was proposed using a three-layer feedforward network. The multi- layer feedforward network can approximate any nonlinear function by using the back propagation (BP) algorithm. A rotor speed estimator was used by Pedro with the multi-layer feedforward network [28]. The observer is only trained off-line by the BP algorithm, so it is not accurate enough for the real time system.

ANN was applied to vector selector as well as state observer in [29]. Based on DTC principle, the neural-network controller is divided into the following five sub-nets, each of which is individually trained: 1) Flux estimation sub-net (supervised) with dynamic neurones; 2) Torque calculation sub-net (fixed weight) with square neurones; 3) Flux angle encoder and magnitude calculation sub-net (supervised and fixed weight) with logsig neurones and tansig neurones; 4) Hysteresis comparator sub-net (fixed weight) with recurrent neurones; 5) Optimum switching table sub-net (supervised) with hard limit neurones. With the simple architecture and inherent parallel computation capability, this ANN DTC scheme minimised the computation delay of each cycle. However, this ANN controller was only built in SIMULINK which is easy to process supervised and fixed weight training.

In [30-31], classical DTC control strategy has been learnt by the generalised mapping regressor (GMR) network and then the performance of the neural controller has been verified by both numerical simulations and experiment with a properly devised test bench. Different from most of previous papers, an experimental test bench was set up and then the good function of the GMR was experimentally verified. The GMR neural network's inputs include the torque error, the stator flux linkage error and the sector in which it lies, and the output include the voltage space vector to be generated by the inverter. The GMR then replaces the switching table as well as the hysteresis comparators, resulting in an easy implementation.

In 2006, an ANN based DTC controller was proposed for PMSM in [32]. A comparison between BP network and radial-basis function network (RBFN) was made. The flexible neural network structures were used to implement a DTC system for an inverter-fed PMSM drive. Based on the fundamental principle of DTC, an individual training strategy is employed for the neural network controller design. The results obtained using simulations concluded that the RFBN presents a good alternative. It was proved that ANN controller is possible to replace switching table of the DTC for PMSM and achieve high torque response.

D. New Tendency of DTC Controller Design

Recently, researchers are trying to develop DTC schemes by combining two or three of above techniques together. As mentioned, FDTC and VSC perform well at controller design but limited by the nonlinear uncertainties and parameter estimation error. On the other hand, ANN is widely used to observe the motor state and estimate the stator resistance. However, there are few applications about ANN DTC controller because it is hard to train a network online without an accurate controller.

A PMSM DTC driver based on neural networks and multi fuzzy controllers was presented in [33], by replacing the conventional hysteresis controller with fuzzy controller and estimating the stator resistance on line using the learning capability of neural networks. To tune the weights and biases of the neural networks online, another fuzzy controller is adopted. It can combine the capability of fuzzy reasoning in handling uncertain information and the capability of neural network in learning from processes. On the other hand, there are also attempts to develop DTC controller based on adaptive neural network or sliding mode ANN as well as fuzzy neural network (FNN). In [34], a sliding mode indirect torque controller was designed and the system stability is proved by using the Lyapunov function. Based on the uncertainty of parameters and disturbance's range, a kind of parameter neural network and sliding mode controlling method is utilised to reduce chattering. This parameter NN is trained online and keeps identifying the parameters of the sliding mode controller.

The modern control strategies can provide good solutions to nonlinear system or nonlinear factors of system. However, as mentioned above, there are still some limitations of themselves that make it difficult to build an ideal motor drive system with any of them only. It is a tendency to combine more than one control method in a drive system to handle the parameter variation and other uncertain errors in order to achieve good performance.

IV. CONCLUSION

This paper presents a comprehensive review on DTC strategies for PMSM drives. The DTC represents a viable alternative to FOC, although there are still some problems such as torque and flux ripples. The reported DTC controllers have been divided into two groups: hysteresis controller based solutions and modern control theory based controllers. To reduce the torque ripple, the first group are investigated to mainly improve the vector modulation method with a simple structure for implementation. The second group are usually based on the modern control theories with a complex algorithm to handle nonlinear uncertainties, which can be used for high performance drive systems.

Based on the survey and analysis, the possible further work for improving the DTC schemes for practical high performance drive systems has been discussed.

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