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A review of direct torque control development in various multilevel inverter applications

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ABSTRACT

Multilevel inverter (MLI) is commonly utilized in direct torque control (DTC) for medium and high-power applications. The additional voltage vectors generated by MLI can be manipulated to achieve the optimal selection for the inverter switching states in the DTC control systems. Previously, a review of DTC which focused more on the two-level inverter for AC machine as well as a review of multilevel converter in industrial applications had been implemented individually. However, a review on DTC development in MLI was insufficient in both papers. Therefore, this paper aims to give a comprehensive review of the improvement of DTC via various MLI applications. It is reviewed according to the applicable multilevel inverter topologies in the DTC system. The comparison of DTC by using conventional and multilevel inverter is synthesized. Thus, this review paper will hopefully lead researchers in further research activities actively.

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1. INTRODUCTION

Direct torque control (DTC) scheme introduced by Takahashi and Noguchi in 1896 [1] has employed two-level or voltage source inverter (VSI) circuit on its prior application with the aim to control the torque and flux performance by using the appropriate voltage vector. It gains attention in industrial application when the AC machine is the employed in this control scheme. Thus, it gains a lot of attractions from many researchers for implementing the several development of DTC [2]-[7]. Therefore, several review papers, [8], [9] have been published but they are more emphasized to the development on the prior or conventional DTC application.

Meanwhile, multilevel inverter (MLI) is widely applied in the industrial application due to some attributes such as high voltage capability, reduced current harmonic and switching voltage stress the like [10]-[13]. Despite of these advantages, they are interpreted into the review paper that explain the MLI's contribution into industrial application in general [14]-[16]. MLI is also well adapted in DTC due to its abundant voltage vector rather than the limited voltage vector in VSI. Thus, the DTC performance can be more optimized by using the variety control of MLI. However, a review on DTC development adapted by MLI is lack emphasized in the aforementioned review paper. Thus, this paper aims to give a comprehensive review of the improvement of DTC via various MLI applications as highlighted in Figure 1. The comparison of DTC by using conventional inverter (VSI) and MLI is synthesized. Thus, it will help lead researchers in to further research activities.

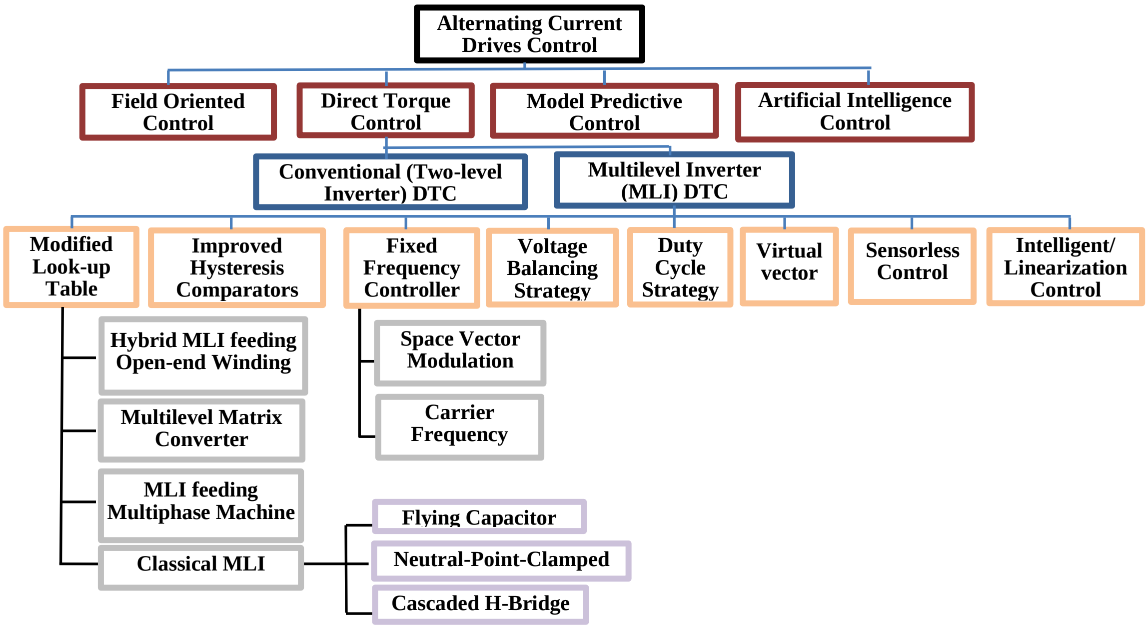


Figure 1. A diagram review of DTC via implemented of MLI

2. CONVENTIONAL DTC

The structure of DTC drive control proposed in [1] is illustrated in Figure 2. It consists of torque and flux estimators, a coupled of hysteresis comparators, look-up table and two-level inverter. A pair of control structure as aforementioned obviously controls the two independent variables such as stator flux and electromagnetic torque using two-level and three-level hysteresis comparators. In the previous implementation of DTC, the two-level inverter is employed to drive the AC machine as shown in Figure 3(a). The circuit produces eight voltage vectors which are classified into two zero voltage vectors (V0 and V7) and six active voltage vectors (V1-V6). This is further displayed by the mapping vectors in Figure 3(b). A basis of look-up table DTC is constructed in Table 1 where the voltage vectors are mapped into the sector, the error status of torque (Te_{stat}) and stator flux (Ψs_{stat}).

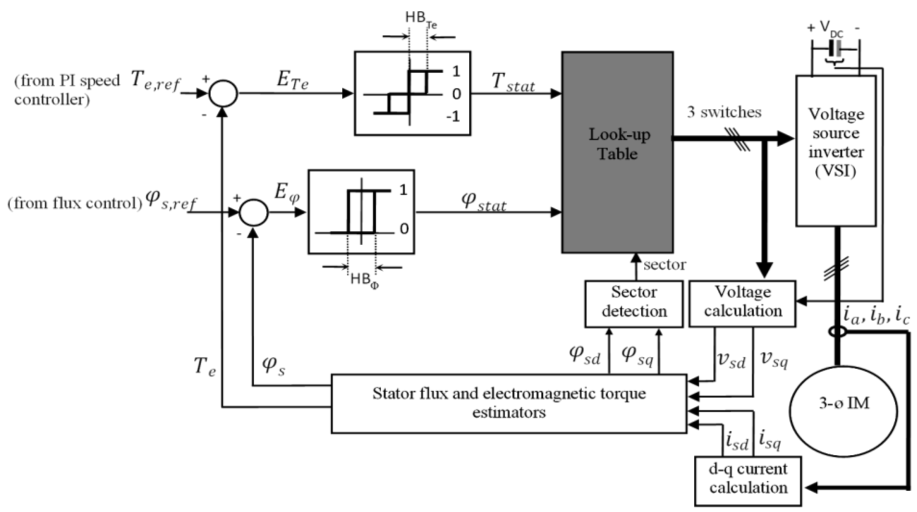
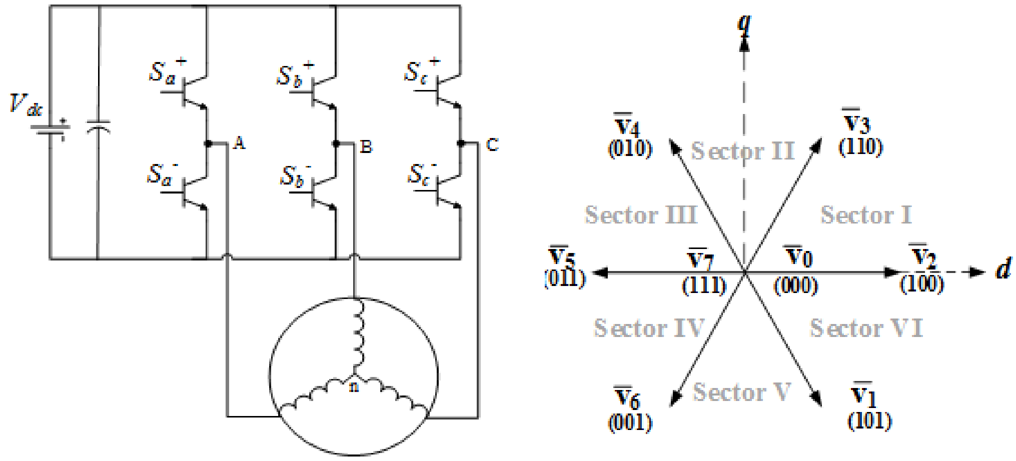


Figure 2. Structure of conventional DTC [1]



(a) (b)

Figure 3. (a) Two-level inverter circuit and (b) Space vector diagram [1]

Table 1. The look-up table of conventional DTC [1]

Ψs stat	Te stat	sector I	sector II	sector III	sector IV	sector V	sector VI
1	1	V_2 (100)	V_3 (110)	V_4 (010)	V_5 (011)	V_6 (001)	V_1 (101)
	0	V_0 (000)	V_7 (111)	V_0 (000)	V_2 (100)	V_0 (000)	V_2 (100)
	-1	V_6 (001)	V_1 (101)	V_2 (100)	V_3 (110)	V_4 (010)	V_5 (011)
0	1	V_3 (110)	V_4 (010)	V_5 (011)	V_6 (001)	V_1 (101)	V_2 (100)
	0	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)
	-1	V_5 (011)	V_6 (001)	V_1 (101)	V_2 (100)	V_3 (110)	V_4 (010)

3. MULTILEVEL INVERTER DTC

3.1. Modified look-up table

The attributes of conventional DTC are still when applied the MLI except it will increase the voltage vectors. Aside voltage vectors, other variables such as sector, torque and flux error status included in the look-up tables are also susceptible to the traits of MLI. In the classical MLI *i.e.*, flying capacitor (FC), neutral point clamped (NPC), and cascaded H-bridge (CHB) topologies, the voltage vector mapping is enlarged due to the increasing number of levels. Generally, the three- and five-level inverter will generate 64 [17] and 512 [18] voltage vectors respectively. This flexibility encourages the optimal selection of voltage vector from the look-up table [17]-[19]. In FC-DTC, the lookup table was altered as the number of sector was increased into 24 sectors [20]. Meanwhile in NPC-DTC, the modified look-up table based on the optimum current ripple principle and the look-up table with a uniform control method were proposed in [21] and [22] respectively.

Further in the modern topologies of MLI, the hybrid MLI feeding open-end winding (OEW) was introduced in drive application in 1993 [23]. This is done by floating the neutral point of motor winding to connect the dual two-level inverters into both ends of motor windings. Some improvements of its look-up table has been discussed in [24]-[27] related to the extra operation, modified look-up table and improvised switching table. On the other hand, the matrix converter (MC) on DTC was introduced in the early 2000’s [28]. Its construction is based on the bidirectional switches performed the sinusoidal input/output current related to the variable input power factor. The study of conventional MC-DTC table can be referred to in [28], [29] followed by its development in [30], [31] through the twelve-sided polygonal structure and sub-region strategy. MLI feeding multiphase machine also brings interest to the drive application that enables employment of the five-phase, six-phase or even higher phases onwards. Further, the research development of five- and six-phase employed in DTC can be referred in [32]-[35] and [36]-[39] correspondingly.

3.2. Improved hysteresis comparators

Hysteresis comparator is a core in the DTC drive. In the classical DTC, the three-level hysteresis comparator yields the error status of torque of +1, 0 and -1 whilst for the stator flux, the two-level hysteresis comparator yields the flux error status of +1, and 0. They still remained in the NPC-DTC [40]. The availability of voltage vectors in MLI tends to increase the level of hysteresis comparators [18], [35]. For instance in [18], the five-level CHB-DTC had proposed eight-level torque and five-level flux comparator using seven and four two-level hysteresis comparator respectively. The eight-level torque hysteresis comparator was denoted by the error status of torque of +3, +2, +1, +0, -0, -1, -2 and -3. Meanwhile, the five-level flux hysteresis comparator was denoted by the flux error status of +2, +1, +0, -0, -1 and -2. Typically, the highest value of error status (positive or negative) was recommended for the large voltage vectors to achieve the fast-dynamic torque response. The lowest value (positive or negative) however was recommended for the small or zero voltage vectors to reach the slow torque response as well as minimize the torque ripple [35].

Further analysis regarding the modified hysteresis comparator was discussed in [41] by using three- and five-level CHB-DTC. The three- and five-level CHB have employed the two- and five-level hysteresis comparator respectively. Both levels have applied seven-level hysteresis comparator for torque controller. Figure 4 shows the proposed method of five-level CHB-DTC. This proposed scheme is contributed into the NPC-DTC [42], matrix converter [43] and multiphase machine [39] with the aim of minimizing the steady-state error and torque ripple, as well as harmonic current.

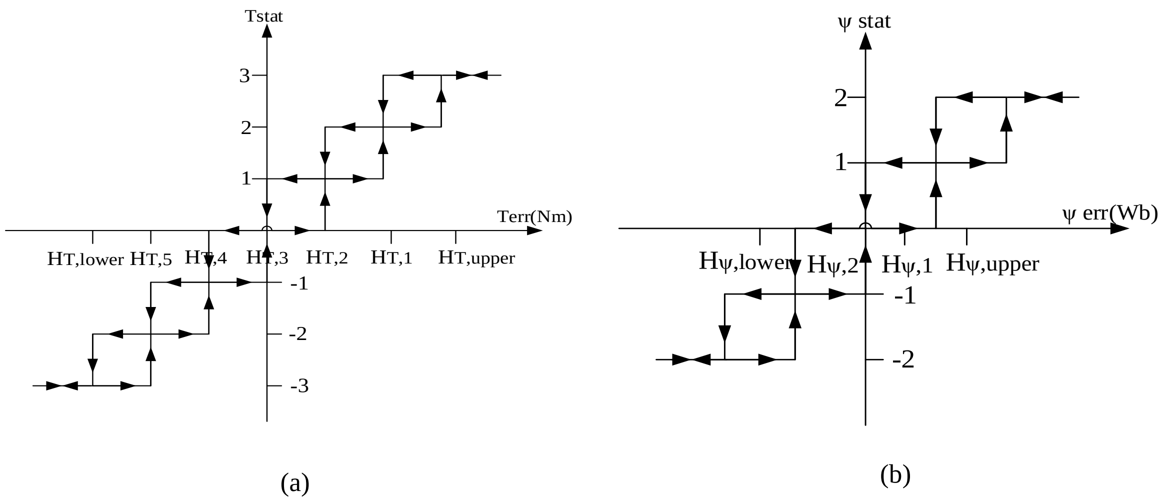


Figure 4. Hysteresis comparator of (a) 7-level for torque and (b) 5-level for flux in MLI [41]

3.3. Fixed frequency controller

The inconsistency of switching frequency in DTC is mainly caused by the torque comparator [44]. Basically, the slope of torque contains several variables such as stator voltage, speed, stator flux and rotor flux. The uncontrollable operating speed may contribute to the unpredictable switching frequency. Thus it is difficult to optimize the DTC performance [9]. Some suggestions have been offered to solve this problem such as Space Vector Modulation (SVM) and carrier frequencies.

SVM was a part of the modulation strategy for DTC in 1992 by Habetler [45]. It controls decouple electromagnetic torque and stator flux by using PI controller to produce the d- and q- axis voltage. The stator flux angle which is applied in SVM strategy is calculated from the estimated torque and stator flux. Figure 5(a) shows an example of the reference voltage vector d-q which occurs on one of the sectors in the conventional DTC [46]. In the particular sector, the reference voltage vector is located between two adjacent vectors and zero vector with their stipulated time after which the duty cycle is computed to generate the symmetrical switching of SVM.

SVM strategy was extended by using NPC inverter as such in [47], [48]. For example in [48], a new simplification algorithm was constructed for the classical SVM technique. The g-h reference frame or 60° reference frame that neglected the trigonometric functions to be applied by the classical SVM. Therefore, six triangular sectors were performed by the space vector diagram. However, in MLI, each triangular sector was divided into four small triangular regions as shown in Figure 5(b). Thus, the three vectors nearest to the reference vector among the regions were chosen for the SVM computation. By utilizing the g-h reference frame, the reference vector values of u_{sh} and u_{sg} could be determined by several rules declared in [48]. The SVM strategy has been further improved in CHB-DTC [49], hybrid MLI feeding OEW- DTC [50]-[52], MC-DTC [53] and the multiphase machine as in [54].

As the substitute of SVM, the fixed or constant switching frequency could be achieved by using triangular waveform or carrier frequency proposed by Idris in 2002 [55], [56]. It replaced the hysteresis comparator of torque controller in DTC and neglected the complicated operation such as SVM. Illustrated in Figure 6(a) is the conventional DTC where the proportional integral (PI) controller regulated the torque error before comparing with the two compliment phases of triangular waveforms which contain the carrier frequencies. This approach was prolonged into MLI as in [3], [57], [58]. As employed in CHB-DTC [57], the constant frequency controller was added with six comparators and six triangular waveforms as shown in Figure 6(b) finally for creating the torque error status.

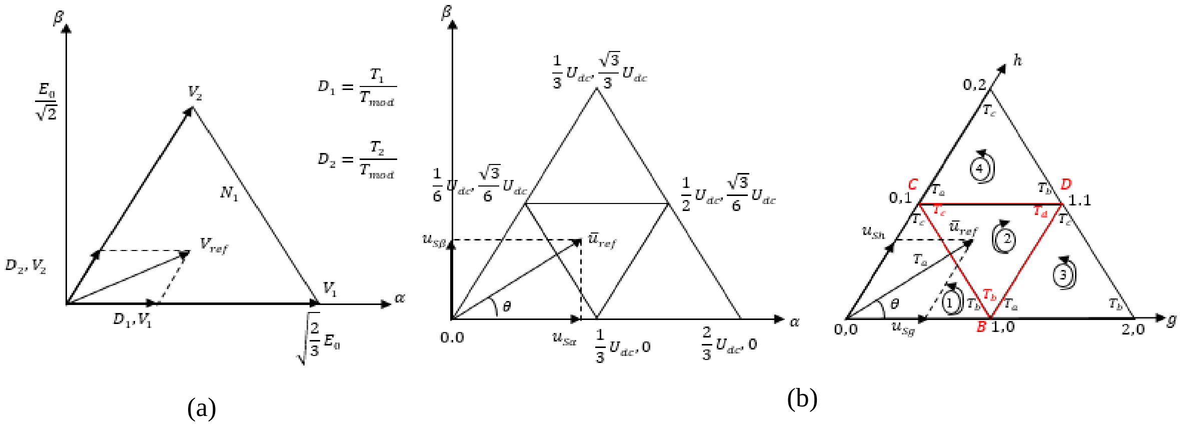


Figure 5. SVM strategy, (a) The reference voltage vector projection on V1 and V2 in sector 1 in conventional DTC [46] and (b) SVM strategy in MLI in sector 1 through four small triangular region coverted from a-b (left) into g-h (right) reference frames [48]

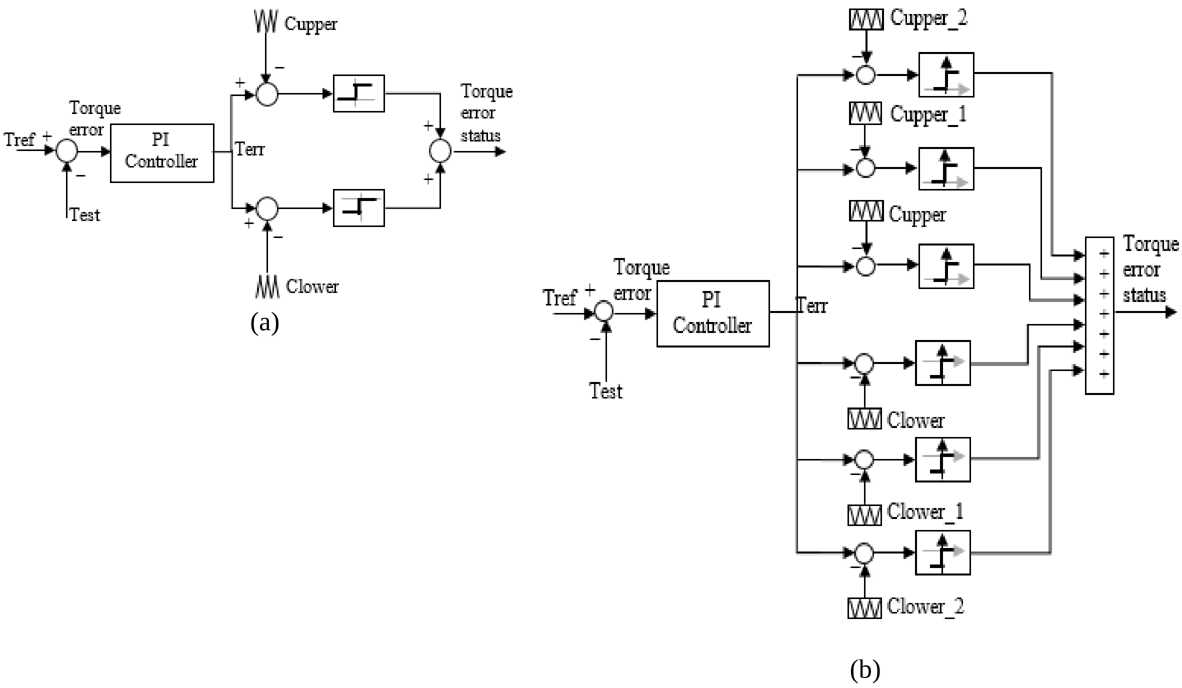


Figure 6. Carrier frequency controller, (a) conventional DTC [55], [56] and (b) Proposed carrier frequency controller in MLI by [57]

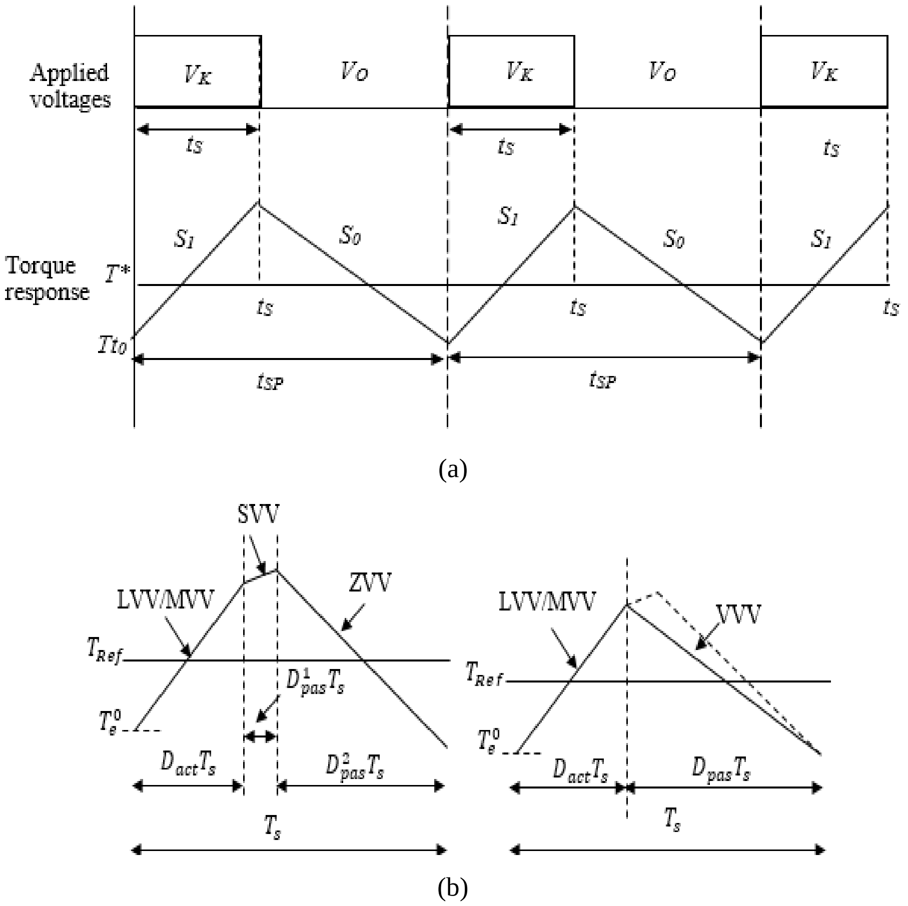


Figure 7. Duty cycle based strategy, (a) conventional DTC [59] (b) DTC using MLI applying conventional method (left) and modified method (right) by[4]

3.4. Duty cycle strategy

Duty cycle based strategy was a typical method for reducing the torque and stator flux ripple in the conventional DTC as introduced by Kang in 1999 [59]. It applied two voltage vectors (one active, V_K and one zero voltage vector, V_O) within one interval switching, t_{SP} as shown in Figure 7(a). The duty cycle have been developed by using conventional DTC in [60], [61]. Zero voltage vector and two active voltage vector were employed in [60]. However, it reduced the reliability and capability of DTC. Meanwhile in [61], the three voltage vectors were applied to minimize the torque and stator flux ripple at each switching period. However, the switching losses were increased due to the additional one voltage vector.

In MLI DTC, the duty cycle strategy was developed in [4], [62], [63]. As introduced in [4], the manipulation of voltage vectors within one switching interval was easily determined through the extra voltage vectors. The variety of voltage vectors could be classified into four categories namely (i) large (LVV), (ii) medium (MVV), (iii) small (SVV) and (iv) zero voltage vector (ZVV). In the normal speed operation as illustrated in Figure 7(b)(left), the torque ripple profile was performed using the vector combination of LVV/MVV-SVV-ZVV as proposed in [4]. Due to the complex implementation to compute the duty ratio, the voltage vectors of SVV and ZVV were combined to perform a virtual voltage vector (VVV). As a result, the vector combination of LVV/MVV-VVV was simplified like a normal profile of torque ripple as shown in Figure 7(b)(right). The relationship of torque slope and machine speed was also studied in [4] that encouraged the derivation of the slope equations for particular vectors for such the combination of LVV-VVV, MVV-VVV and SVV-ZVV.

3.5. Voltage balancing

The issue of voltage balancing was mainly concerned in NPC-DTC and FC-DTC. This was due to the built-in capacitors which was located parallel to the input DC voltage and switching devices. The capacitors are exploited by the fluctuation of DC voltage triggered by the voltage deviation flowing the three phase AC machines or loads. As a result, it may lead to the severe condition on input DC voltage of inverter circuit. Several methods to solve the matters had been suggested by researchers in [4], [64]-[67].

A control algorithm of voltage balancing was proposed in [64] for controlling the signals in the inverter-leg by using the input of required voltage level, capacitor voltage states and current direction. Meanwhile in [4], [65], the extra look-up table was built as a two-level hysteresis comparator was added to control the voltage deviation through the DC link capacitors in the DTC systems. For instance in [65], the proposed method was shown in Figure 8. The voltage balancing method which focused on the line voltage harmonic had resulted in a slight increase of current harmonic compared to the basic condition in [66].

3.6. Virtual vector

The virtual vector (VV) principal was first introduced in 2002 by Tan [68] through the three-level NPC inverter. It is a part of synthesized vector that is identical with the conventional SVM except it has a fixed position. In [68], a modified look-up table was performed by comprising of 12 virtual vectors and zero vectors in low-speed region. This concept was improved in [69] by solving the large fluctuation of neutral point voltage and eliminating the voltage shifting on the previous NPC-DTC.

Multiphase machine had also applied the VV concept [33], [39]. For synthesizing the VV, two methods are explained in [33]; 1) the volt-second balance technique and, 2) flux angle in the x-y plane. Most of the researchers preferred to employ the volt-second balance technique to remove the flux in x-y plane. By using the volt--second balance technique, the synthesized of large VV was produced by merging the voltage vector 6 (large vector) and 15 (medium vector). Meanwhile the small VV was produced by merging the voltage vector 22 (small vector) and 15 (medium vector). Consequently, the synthesized of VV large (V_{11} - V_{20}) and small (V_1 - V_{10}) voltage vectors were constructed as illustrated in Figure 9.

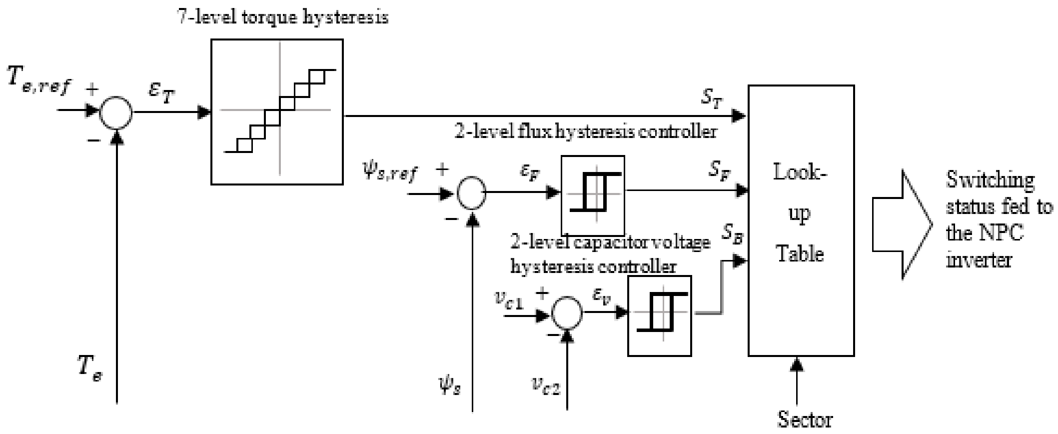


Figure 8. Voltage balancing strategy in NPC-DTC [65]

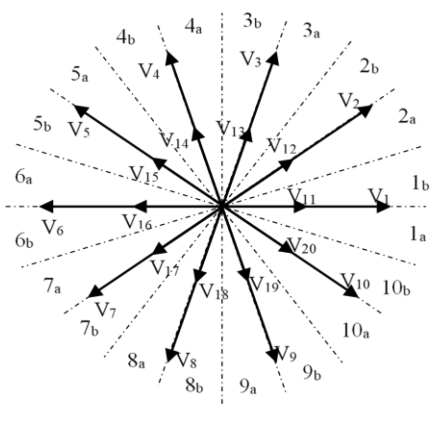


Figure 9. Virtual vector of five-phase machine [33]

3.7. Sensorless control

Normally in the DTC application, the knowledge of rotor speed was ignored in the implementation the flux stator estimation. This is due to the availability of sampled values from the stator voltages and current as described by Monti in 1998 [70]. The stator voltage model employed in flux stator estimator produced the drawback at low-speed regions caused by the small magnitude of induced rotor voltages and currents. It was due to the stator flux failure to regulate at very low frequency and the existence of integration operation. Hence, numerous solutions had been suggested such as full-order observer, adaptive scheme, extended Kalman Filter the like [70], [71]. Nevertheless, this problem remained unsolved in MLI.

Generally, the adaptive observer was often utilized because of the abandonment of open-loop integration and the insertion of available mechanism in the stator resistance estimation [72]. An example of the sensorless DTC using speed adaptive flux observer was shown in Figure 10 by using NPC-DTC. In [73], the combination of flux observer and speed observer was employed in the MC-DTC. Elsewehere, another sensorless method called as a parameter strategy was proposed by Lee [74]. By assuming a constant rotor speed, a parameter estimation was produced by the conversion of state estimation when applied the error model. The Lyapunov analysis was utilized to test the stability properties of the estimator. As a result, a good response against the parameter variation was achieved using the proposed method.

Other sensorless methods recommended for multiphase machine-DTC were proposed in [75], [76]. The sensorless control using power measurement was suggested in [75] which involved the calculation of active and reactive power (PQ), and also the variable of arbitrary reference frame multiscalar (x,y). The sensorless method through the combination of flux linkage observer and Extended Kalman Filter (EKF) was presented in [76]. Although the aforementioned method required more calculations and high computational power, but it may achieve the better position and speed estimations due to the high noise-rejection ability.

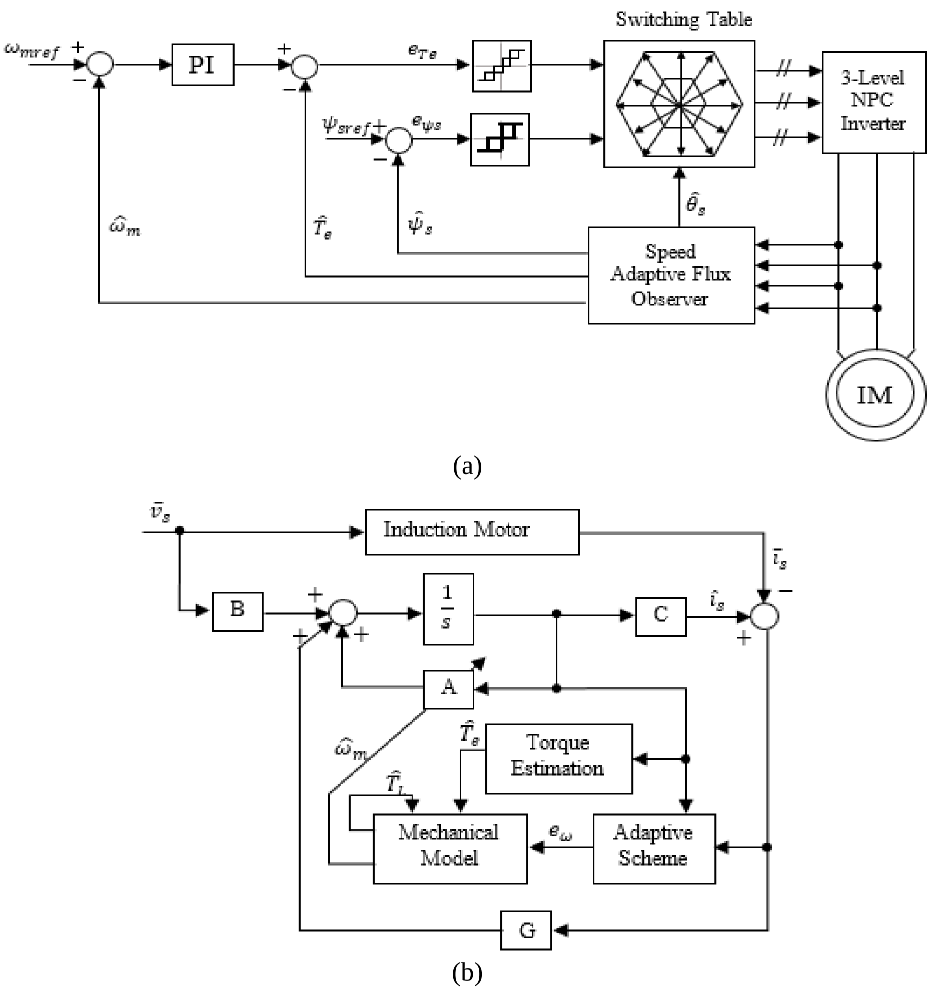
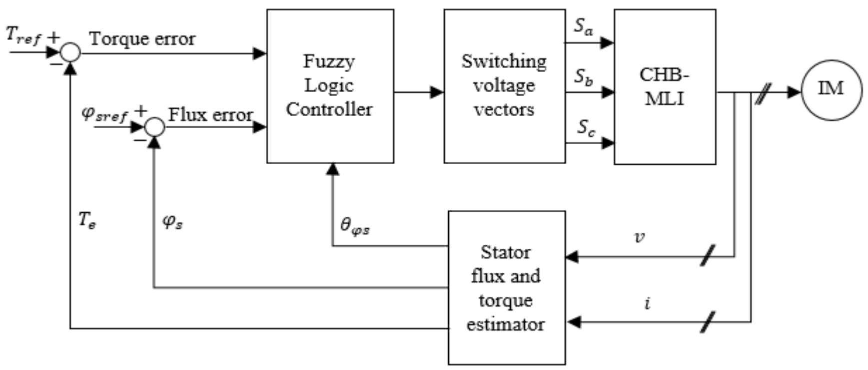


Figure 10. Sensorless DTC using speed adaptive flux observer, (a) Block diagram of sensorless NPC-DTC and (b) Structure of speed adaptive flux observer [72]

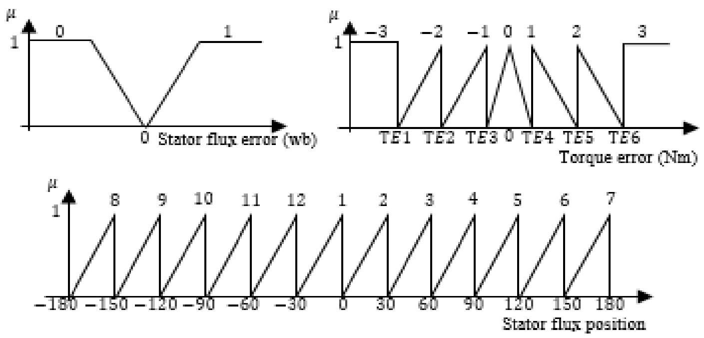
3.8. Intelligent/digital control

The artificial intelligence (AI) control such as fuzzy, neural network, generic algorithm and the like applied the advanced and modern algorithm to solve the drawback of DTC. Fuzzy logic as the basic intelligent control was proposed by Bird in 1997 [77]. It has still been employed in conventional DTC recently [78]. In the MLI, this control strategy was extended as suggested in [47], [79], [80] whereby it replaced the hysteresis comparators to control either speed, stator flux or electromagnetic torque. The structure of fuzzy logic controller by using CHB-DTC is illustrated in Figure 11 [79]. Elsewhere, the fuzzy logic was adapted in MC-DTC [80].

Neural network (NN) based on neurons concept contributes well in conventional DTC [81], [82]. Meanwhile in MLI, several developments of neural network are done [83]-[86] such as nine sub-nets that contained 12 layers and 134 neurons in MC-DTC [83], four- subnetwork in NPC-DTC [84] and three neurons of hidden layer in five-phase machine DTC [85]. Besides, the radial-basis function network (RBFN) in MC [87] is applied to achieve a simple structure of control algorithm and neglect the limit condition on the design constant as the purpose of stability. Another control strategy called as feedback linearization (FBL) technique fed on DTC was suggested in CHB [88]. The aim of this strategy was to convert the nonlinear system into the linear system by involving some of the algebraically transformation. On the other hand, the combination of DTC control and non-linear control was also developed in multiphase named as backstepping control in [89].



(a)



(b)

Figure 11. Structure of fuzzy logic controller by using CHB-DTC, (a) Fuzzy logic controller for CHB-DTC represented by block diagram and (b) Membership function of fuzzy logic controller [79]

4. RESULTS AND DISCUSSION

Overall, the improvement of DTC by using the variety topologies of MLI have been reviewed including the proposed strategy and method with the aim of achieve the good performance of DTC. Those approaches are available and relevant to be employed in the AC drive system according to the number of researches. Besides, the critical review of this paper is summarized in the Table 2 as the features discussed are look-up table, hysteresis comparator, space vector modulation, carrier frequency, duty cycle, voltage balancing, virtual vector, sensorless control and AI control. As compared to the two-level inverter, the complex implementation, extra cost and increase switching devices possessed by MLI are remunerated with the superior and excellent DTC performance.

Table 2. The comparison features of DTC by using conventional and multilevel inverter

Features	Terms	Two-level inverter DTC	Reference	Multilevel inverter DTC	Reference
Look-up table	Size of voltage vectors	small	[1]	large	[17]/ [18]
Hysteresis comparator	Number of levels of Flux/Torque	two/three	[1]	five/seven	[41]
	Range of Hysteresis bandwidth	limited		multi	
Space vector modulation	Number of triangular fractals in one hexagonal diagram	six	[46]	64	[48]
	Time adjacent of nearest voltage vector	long		short	
	Precision of voltage vector projection	low		high	
Carrier frequency	Number of triangular carrier frequency	two	[55]	six	[57]
Duty cycle	Number of voltage vectors in one-time interval switching	two	[59]	two/three	[4]
Voltage balancing	Number of voltage vector caused the unbalanced	none	-	two	[65]
Virtual vector	Number of the merging voltage vector	none	-	two	[33]
Sensorless control	Electrical and mechanical equation model	unchanged	[70]	unchanged	[72]
AI control such as fuzzy and NN	Size of fuzzy rules	small	[78]	large	[79]
	Size of layers and neuron	small	[82]	large	[83]

5. CONCLUSION

In the adjustable speed drive applications, the DTC drive gains high interest due to its simple and robust attributes. Definitely, DTC requires some improvements to sustain its operation and overcome its weaknesses. One of the improvements is the application of MLI which acquires the extra voltage vectors for optimal selection on the inverter switching. Several features of DTC developments by using MLI have been critically reviewed thus the comparisons between conventional inverter and MLI are summarized. A lot of consideration needs to be emphasized on when designing the MLI in the DTC system. The extra voltage vector acquired by MLI become flexible and reliable in the wide range of power application. Therefore, this review paper delivers the alternative research to those concern in this field to become their future research.

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