Enhanced Direct Torque Control for Doubly Fed Induction Machine by Active Learning Method Using Indirect Matrix Converter

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Abstract

The term Direct Torque Control (DTC) originally is referred to a strategy which provides good transient and steady-state performance but it has also some negative aspects, such as non accuracy of flux, torque estimator, torque and flux ripple caused by non-optimality of switching and imprecision in motor model which are known as an inherent characteristic of DTC. This paper explores reducing of flux and torque ripple with using trial and error actively as a method called Active Learning Method (ALM) in DTC for Doubly Fed Induction Machine (DFIM) which are the motors or generators having twist on both stator and rotor subsequence power is transferred between shaft and system. DFIM is linked to the grid within the stator and the rotor is fed by an Indirect Matrix Converter (IMC). The function of IMC is similar to the direct one, although it has the line and load bridges separated. We analysis the usage of four-step commutation in rectifier stage of IMC to achieve the object of the losses' reduction which are caused by snubber circuit. ALM adopts itself with torque and flux estimators and estimates the outputs with regards to the errors in torque and flux estimation by repetition therefore achieves the object of omitting inaccuracies in control system hence confirming the effectiveness. Another concept in ALM called Ink Drop Spread (IDS) handles different modeling target to predict on the data consequensing a behavior curve in DTC. According to the simulation results, it is proved that a significant torque and stator flux ripple reduction are obtained.

Keywords: Active Learning Method; Direct Torque Control; Doubly Fed Induction Machine; Indirect Matrix Converter.

1. INTRODUCTION

The conventional energy sources are limit and have pollution for the environment, so more attention and interest have been paid to the utilization of renewable energy sources such as wind energy, fuel cell and solar energy etc. Among them wind energy is the fastest growing and most promising renewable energy source due to economically viable [1].

In the field of wind energy generation systems, the wind turbine development shows a tendency to increase the generation power level. According to the variation wind speed, Doubly Fed Induction Machine (DFIM) is a common solution for variable speed wind turbines [2].

Often, the wind energy generation demands good torque dynamic performance as well [2]. Among all methods of torque control developed for the induction machine, the most widely used technique may be classified within the Field Oriented Control (FOC) techniques and the direct control techniques [2]. It seems to be accepted that the direct control techniques first introduced such as Direct Torque Control (DTC) [3] and Direct Self Control (DSC) [4] achieve better steady-state and transient torque control conditions rather than FOC techniques [5],[2].

Direct Torque Control (DTC) accompanies by some problems such as non accuracy of flux, torque estimator, torque and flux ripple caused by non-optimality of switching and imprecision in motor model which are all the inherent characteristics of DTC. To overcome these difficulties lots of papers have been published on solving DTC drawbacks. Some of these papers fuzzified the DTC system inputs and improve its characteristics [6],[7], some else tried to improve the torque and flux estimators [8]-[10].

Active Learning Method (ALM) is a powerful recursive fuzzy modeling without computational complexity. ALM has been proposed as a new approach to soft computing. The concept of the ALM is based on the hypothesis that humans interpret information in the form of pattern-like images rather than in numerical or logical forms. The ALM is modeled algorithmically on the intelligent information-handling processes of the human brain, and it is characterized by computing on the basis of intuitive pattern information [10]-[13].

In the Active Learning Method to model the information, a method called as Ink Drop Spread (IDS) is used. The IDS method is able to deal with various modeling targets, ranging from logic operations to complex nonlinear systems [10]. The IDS method possesses stable fast convergence, and its modeling process, which is based on computing that uses pattern information instead of complex formulas, is simple and efficient [10],[14].

Matrix converters (MCs) have been studied widely since their principle was introduced in 1970[20]. A MC is an AC-AC converter, with m×n bidirectional switch, which connects an m-phase voltage source to an n-phase load . The matrix converter Compared with the conventional AC/DC/AC converter, has some merits such as : eliminating bulky DC link capacitor in it, straightforward Four-quadrant operation, also by controlling the switching devices appropriately, both output voltage and input current are sinusoidal with only harmonics around or above switching frequency [21].

Matrix-converter topologies can be divided into two types, one of them is direct matrix converters (DMC) and another one is indirect matrix converters (IMC) which consists of separated line and load bridges as presented in section [22].

Commutation problem of DMC is reduced considerably by utilize specific current commutation methods. Typically two types of commutations methods have been proposed which don't require snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components. The first method is named rectifier zero current commutation and the second is named rectifier four-step commutation. In these methods, although the losses in snubber circuits and the switching losses in the PWM rectifier can be reduced but a complicated control circuit must be added to synchronize the switching of both the PWM rectifier and the PWM inverter [22].

This research used ALM for DFIM to overcome the problems that were presented to DTC. ALM can adapt itself with torque and flux estimators and estimate the outputs regards to the errors in torque and flux estimations. Also proposed method avoids mathematical complexities of fuzzy like methods so it is faster than conventional methods [10],[14]. From another side for feeding DFIM's rotor indirect matrix converter is used. The benefit of four-step commutation is analyzed in rectifier stage of IMC to achieve the object of the losses' reduction which are caused by snubber circuit.

2. DIRECT TORQUE ONTROL PRINIPLE

Fig.1 shows the schematic of Direct Torque Control of DFIM. Stator winding of induction machine is connected directly to the grid and the rotor is fed by converter that is also connected to the grid. The main goal of the DTC is directly control the rotor flux and the electromagnetic torque of the DFIM with Choosing the best voltage vector.

As shown in fig.2, the position of the rotor flux is divided into six sectors. There are also 8 voltage vectors which-correspond to possible inverter states. These vectors are shown in fig.2. There are also six active vectors $V_1 - V_6$ and two zero vectors V_0, V_7.The torque rotor flux equation of doubly fed induction machine is as follows:

$$T_{em} = \frac{3}{2} p \frac{L_h}{\sigma L_s L_r} |\Psi_r||\Psi_s| \sin \theta \qquad (1)$$

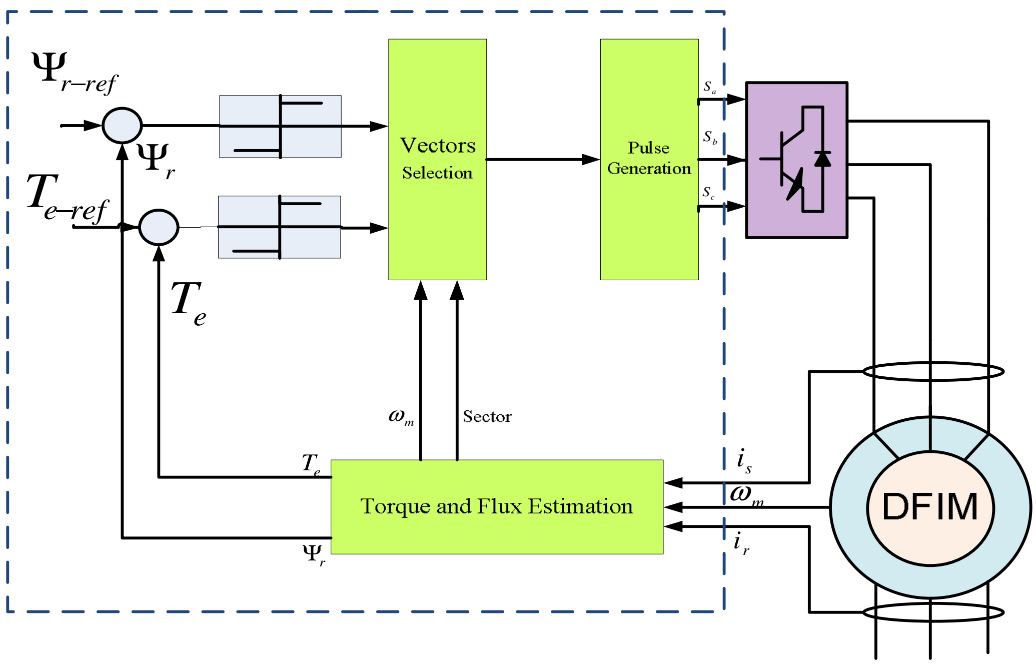

FIGURE 1: The diagram of the DFIM direct torque control system

Where $\sigma = 1 - \frac{{L_h}^2}{L_s L_r}$ is the leakage coefficient. L_s and L_r are the stator and rotor inductance, L_h is mutual inductance, R_r is rotor resistance and θ is phase angle difference between Ψ_r and Ψ_s. As the stator winding of DFIM is connected to power grid, by ignoring the voltage drop of stator winding resistance and the fluctuation of supply voltage, one can appropriately consider the magnitude of the stator flux to be constant and rotate at synchronous speed [15]. Therefore, according to equation (1), we know that the torque control of wound rotor doubly-fed machines can be realized through adjusting the rotor flux vector. Furthermore, in the case that the rotor flux $\overline{\psi_r}$ has a circular trajectory, T becomes the function of phase angle θ. T increases as θ increases. Conversely, T decreases as θ decreases. Therefore, the control of the torque/speed can be realized through adjusting the phase angle θ.

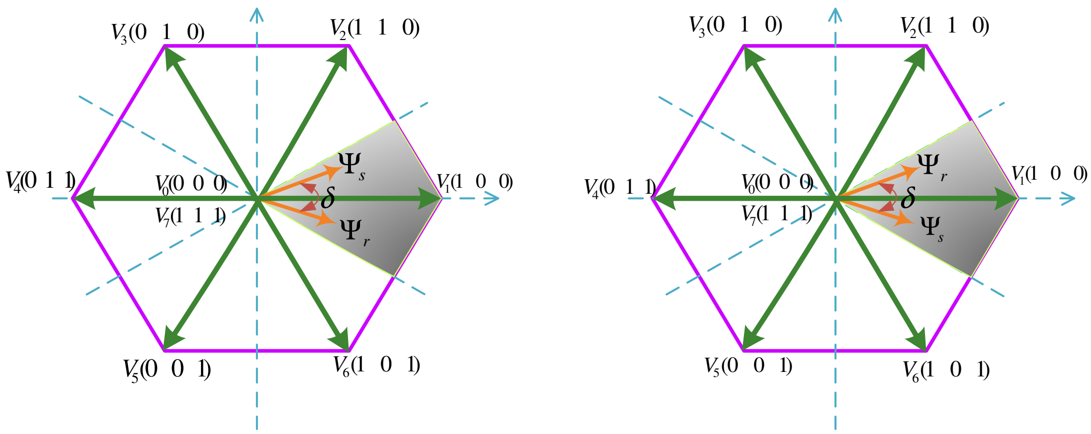

FIGURE 2: Flux space vectors in the rotor reference frame, in motor and generator modes. (a) Motor mode, (b) Generator mode

Considering to Fig.1 to find out which vector is appropriate for DTC drive, first by comparing the flux and torque reference values with the calculated ones, Error values of them are determined. Second the error values are applied into two-level hysteresis comparators. The output of both two-level hysteresis comparators that show flux and torque should be increase or decrease. According to the operation condition that can be generator or motor mode, sector that rotor flux is located and based on analysis above the selection of rotor voltage vector selected by table I and II.

H_{Te}		1	0	-1	1	0	-1
Rotor Flux Sector	1	V_6	V_0	V_2	V_5	V_7	V_3
	2	V_1	V_7	V_3	V_6	V_0	V_4
	3	V_2	V_0	V_4	V_1	V_7	V_5
	4	V_3	V_7	V_5	V_2	V_0	V_6
	5	V_4	V_0	V_6	V_3	V_7	V_1
	6	V_5	V_7	V_1	V_4	V_0	V_2

TABLE 1: CLASSICAL DTC LOOK-UP TABLE FOR MOTOR MODE[15]

H_{Te}		1	0	-1	1	0	-1
Rotor Flux Sector	1	V_6	V_0	V_2	V_5	V_7	V_3
	2	V_1	V_7	V_3	V_6	V_0	V_4
	3	V_2	V_0	V_4	V_1	V_7	V_5
	4	V_3	V_7	V_5	V_2	V_0	V_6
	5	V_4	V_0	V_6	V_3	V_7	V_1
	6	V_5	V_7	V_1	V_4	V_0	V_2

TABLE 2: All CLASSICAL DTC LOOK-UP TABLE FOR GANARATOR MODE

3. INDIRECT MATRIX CONVENTOR

Indirect matrix converter (IMC), which consists of separated line and load bridges as presented in Fig.4. IMC is similar to the traditional AC/DC/AC converter system and to previous proposed capacitorless DC link circuits. On the load side, the arrangement has the same conventional inverter as for the AC/DC/AC converter. As a consequence, traditional PWM methods may be used to generate the output voltage waveform.

However, in order to ensure proper operation of this converter, the DC side voltage should always be positive. On the line side, the converter has a rectifier which is similar to traditional one except that the switches are all bidirectional [22]. Typically two types of commutations methods have been proposed which don't require snubber circuits for a IMC.

The first method named rectifier zero current commutation and the second method named rectifier four-step commutation. In these methods, although a complicated control circuit must be added to synchronize the switching of both the PWM rectifier and the PWM inverter but the losses in snubber circuits and the switching losses in the PWM rectifier can be reduced [21]. In this paper, four-step commutation method in the rectifier stage is used. In four-step commutation method, direction of output current and value of input voltage determines the sequence of switching and the commutation reliability.

The process of commutation between phase *A* and *B* is explained with Fig.3. phase A connects to rectifier output through IGBT of switch S_{11} and diode of switch S_{12} . At this point, as it is shown (dotted lines in fig. 3.a) current does not pass from other transistors and diodes. When $i_{DC} > 0$ the following four-step switching sequence is: 1) turn off S_{12} ; 2) turn on S_{31} ; 3) turn off S_{11} ; 4) turn on S_{32} . When $i_{DC} < 0$, the following four- step switching sequence is: 1)turn off S_{11}; 2)turn on S_{32} ; 3)turn off S_{12} ; 4)turn on S_{31} [22].

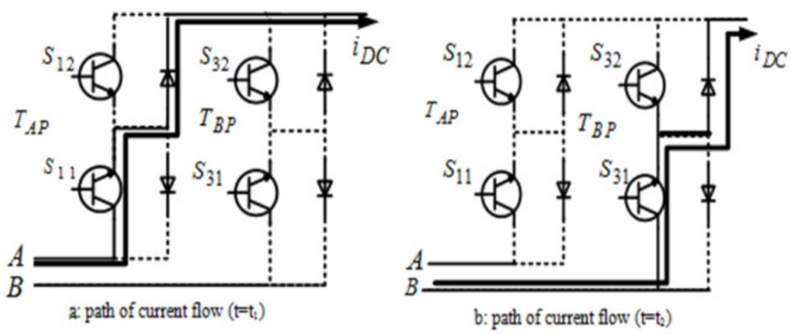

FIGURE 3: Four-Step Commutation Methode Block Diagram[15]

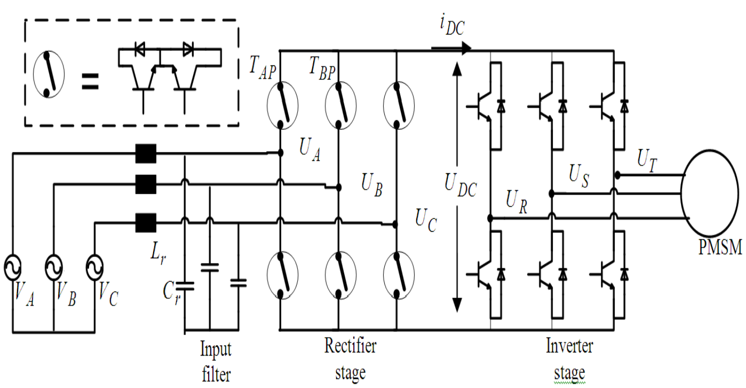

FIGURE 4: Indirect Matrix Converter Structure[15]

4. ACTIVE LEARNING METHOD (ALM)

Active Learning Method (ALM) is a new fuzzy modeling method which has been introduced by Bagheri Shouraki and Honda (1997a).

In contrast to the humans, when human learns an object, in the first step, he grasps its characteristics from much information which apparently looks disorderly, and finds out its tendency, then he finds out the connection with the knowledge formerly learned and he stores it together with the relationship in his brain. The same is true with ALM. When learning the action of a system, it starts from grasping the input-output relations. The input-output data of the object system are collected and the system is modeled. And while memorizing the knowledge, the input-output data are further collected by trial and error, and the system is modeled using the past knowledge and the data. This process is repeated[18].

Active Learning Method is the learning mode in which the learner improves the performance by acquiring information from the behavior of his own [18]. Actually the concept of the ALM is based on the hypothesis that humans interpret information in the form of pattern-like images rather than in numerical or logical forms, in fact it is algorithmically modeled on the intelligent information-handling processes of the human brain, and it is characterized by computing on the basis of intuitive pattern information [10],[16],[17].

ALM considers the behavior of complicated Multi input Multi output (MIMO) systems as collection of simple systems which are single input single output (SISO) systems and the system is expressed by combining them (Fig.5). In the case of two inputs and one output, for example, the input-output relation is plotted on a three-dimensional space [18].

This modeling method not only is similar to human logical thinking but also avoids mathematical complexity. In this method, the learning is done by mutual action with the environment (Fig.6) and promoted by reinforcement learning. The reinforcement learning originated from animal learning psychology and the optimization method like dynamic programming. In this method, the action is

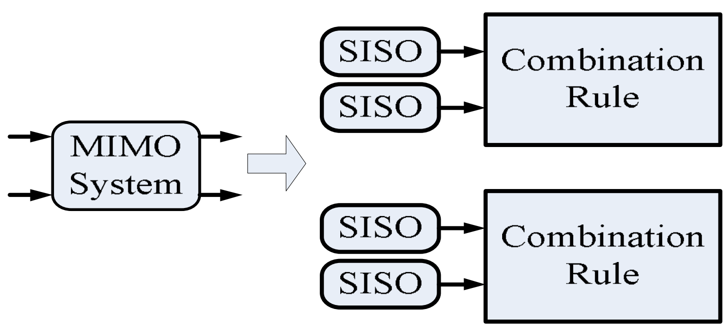

FIGURE 5: Division and Combination of System[14]

reinforced by giving reward or punishment according to the behavior taken in a certain state.
ALM starts with gathering data and projecting them on different data planes. The horizontal axis of each data plane is one of the inputs and the vertical axis is the output. The method called IDS (Ink Drop Spread) which is a processing engine is used to look for a behavior curve, hereafter narrow line, on each data plane. The heart of this learning algorithm is a fuzzy interpolation method which is used to derive a smooth curve among data points [16], [17].

As a matter of fact IDS method is a modeling technique used in the active learning method (ALM), which is a new approach to soft computing. It is characterized by a modeling process which is based on computing that uses intuitive pattern information instead of complex formulas [10].

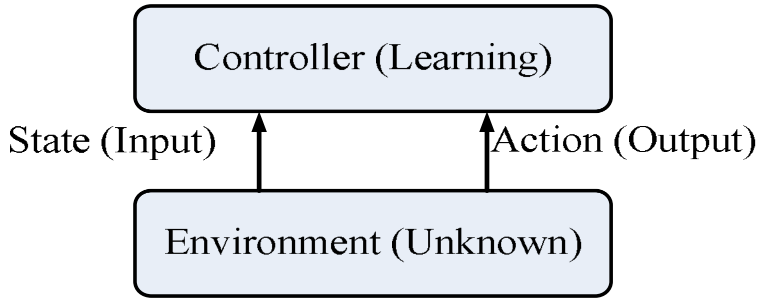

FIGURE 6: Mutual Action with the Environment[14]

5. IV. Ink Drop Spread (IDS)

The basic concept of IDS is to extract the system properties from the input-output data by using fuzzy process. This method searches for continuous possible paths on the interpolated data points on each plane. In this method, we assume that each data point on each data plane is a light source (Fig.7), which has a cone shape illumination pattern. As the distance from these light sources increases, their illumination pattern will interfere and generate new bright areas. The lights interfere with each other and the illuminated pattern appears to show light and darkness. That is, the part where many lights fall is lighter than other part. By combining the light parts continuously, a kind of narrow path expressing the input-output relations can be obtained [18].

By applying IDS method on each data plane, two different types of information would be extracted. One is the narrow path and the other is the deviation of the data points around each narrow path (Fig.8). Each narrow path shows the behavior of output relative to an input and spread of the data points around this path shows the importance degree of that input in overall system behavior. Less deviation of data points around the path presents higher degree of importance and vice versa [18].

Fig.9 illustrates the architecture of an IDS model with two-input, two-partition structure. The IDS model comprises three processing layers. The bottom input layer breaks down input-output data into SISO data, and transfers them to the upper modeling layer. The top inferential layer computes the prediction with the learning data transferred from IDS units. With the exception of the case where a particularly high accuracy is required for an IDS model, the upper layer does not intervene the learning process of IDS units [10],[16]-[19].

Also the spread functions, which show the amount of spread of data on each plane resulting from the effects of other variables, can be calculated using a method presented in [12] by S.B.Shouraki and N.Honda. Then the output of the system can be calculated by (2) [24].

$$y = \frac{\left[\frac{1}{a_1} f_1(x_1) + \frac{1}{a_2} f_2(x_2) + \dots + \frac{1}{a_n} f_n(x_n)\right]}{\left(\frac{1}{a_1} + \frac{1}{a_2} + \dots + \frac{1}{a_n}\right)} \tag{2}$$

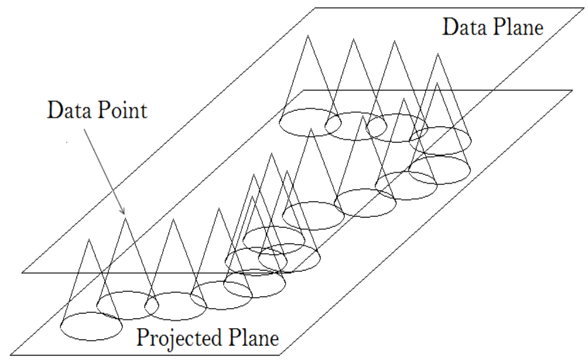

FIGURE 7: Concept of IDS (Ink Drop Spread)[24]

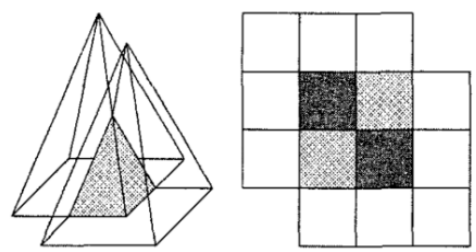

FIGURE 8: Irradiation Pyramid

where
y = the output of system (function)
x1, x2,…, xn = inputs of the system (variables)
f1, f2,… fn = the narrow path functions for plane x-y for each variable
a1, a2,…, an = spread values

6. DTC MODEL BY ALM WITH USING IMC

This research presents and analyses a recommended model of enhanced DTC with the help of ALM, shown in fig10. it uses IMC to feed DFIM's rotor that block control determines unitedly about the appropriate voltage vector in the inverter and rectifier section of IMC. According to the explanations were given about ALM, in this method, with the help of the database, which is obtained by the method of trial and error, the input-output information is collected from the control object and the controller is constructed by the fuzzy-like processing of these data. In the other word some trial inputs are applied to control object and this action is reinforced by giving reward or punishment according to the result. It should be mentioned that trial and error inputs should be

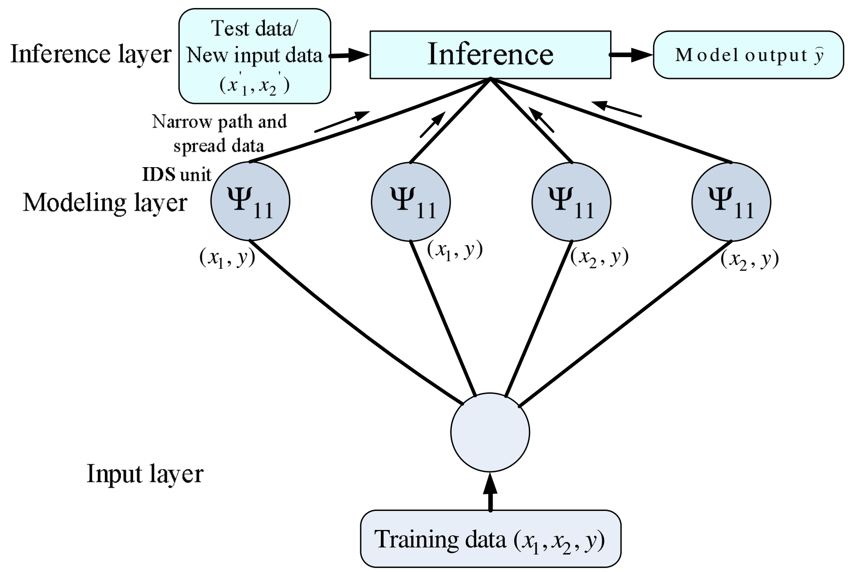

FIGURE 9: Structure of IDS Model[24]

selected so that covers all possible system inputs. On the other hand, by increasing number of trial and error actions, the better model of system can be obtained [10],[14].

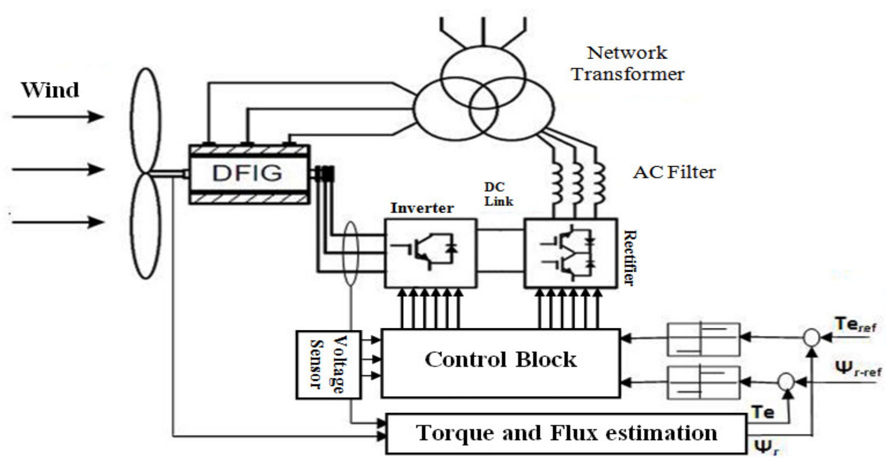

FIGURE 10: DTC using IMC

Regarding the DTC system diagram, shown in Fig10, This research is used IMC to feed DFIM's rotor and the DTC system is a multi input-single output system. Fig. 11 shows the input-output structure of the DTC system control block. According to the ALM basis, this multi input-single output system should be divided into systems with single input and single output (SISO) systems. The DTC control block inputs consist of Torque error, Flux error and rotor Flux angle (position). The rotor flux angle is not considered as an independent input in SISO systems because there is not any direct relationship between rotor flux angle and inverter state (Fig.1). So as mentioned above, the rotor flux is divided into six sectors and this modeling procedure is done for each sector. In the other word, there are 6 couple SISO systems and every couple is for a sector [10].

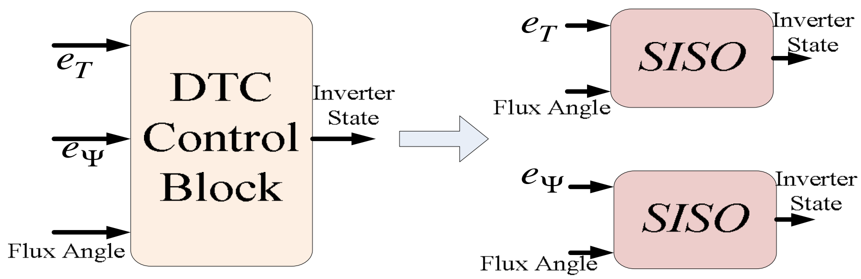

FIGURE 11: Inputs and Outputs of DTC and DTC SISO Models

To apply trial and error inputs Sampling frequency and inverter switching frequency is justified on 8 kHz. To experience different possible errors, torque set value is a random function in proposed model. Some of the sample data obtained by 20000 repetitions are presented in Table 3. This table shows that some inputs lead to improvement in result and some of them worsen the results. So as mentioned above, the inputs which lead to decrease in torque or flux errors should be rewarded and the others should be punished.

These 20000 samples are plotted in a three dimensional space (Fig.12) and the following formula is used to determine the efficiency of each trial action:

$$d_{T_i} = e_{T_i} - e_{T_{i+1}} \quad \text{If} \quad e_{T_i} \geq 0 \tag{3}$$

$$d_{T_i} = e_{T_{i+1}} - e_{T_i} \quad \text{If} \quad e_{T_i} \leq 0 \tag{4}$$

$$M = MAX\,(d_{T_i}) \tag{5}$$

$$E_i = \frac{d_{T_i}}{M} \tag{6}$$

The flux equations and torque equations are same. By equation (6), the efficiency of each applied inverter vector is calculated and Ei determine the magnitude (reward) of each trial and error and its popularity. Any inverter vector with bigger Ei, is reinforced because leads to more improvement in decreasing error. So its relevant vector magnitude in Fig.12 will be bigger [10].

In Fig.12 the plane of trial actions with reward and punishment of data is shown from four different angle of view. The horizontal plane expresses the inverter voltage state and the vertical axis determines the error. The respective correct inverter state of any torque error can be calculated based on these three dimensional plots and the control rules are acquired by these plots, also rules obtained by ALM are similar to classic ones with some minor differences. The rules format is as:
If eT is eT1 and flux sector is α then inverter state is Vm
If eΨ is eΨ1 and flux sector is β then inverter state is Vn
The ALM output in each sector will be achieved by combining SISO models of sector torque and flux errors. DTC total system model is achieved by combining 12 SISO models of six sectors and this combination is based on the sum of adaptability of each SISO model. Equation (7) is used for calculating output by combining SISO outputs [10].

$$y = \alpha_T \times y_T + \alpha_\varphi \times y_\psi \tag{7}$$

Where α is the adaptability of each SISO, determined by the efficiency (Ei) of each case. By this equation the output of a case in sector one will be a compromise of sector one torque and flux error SISO systems outputs [10].

$e_{T\ (NM)}$	eΨ (wb)	Flux Sector	Inverter vector
3.5918541	-0.023571	1	2
0.839314	-0.03453	1	2
-1.42841	-0.18675463	1	2
0.7784831	-0.1834733	1	3
-0.512115	-0.0021443	1	3
1.63797	0.0523732	1	3
-1.346901	0.03453232	1	3
-2.19589	0.0737643	1	5
- 3.219250	-0.0348734	1	5
2.432973	-0.20013	1	5
1.646507	-0.19714	1	5
3.2917926	-0.032432	1	6
1.4556623	-0.0347334	1	6
-0.3716126	-0.042329	1	6

TABLE 3: SOME SAMPLE TRIALS

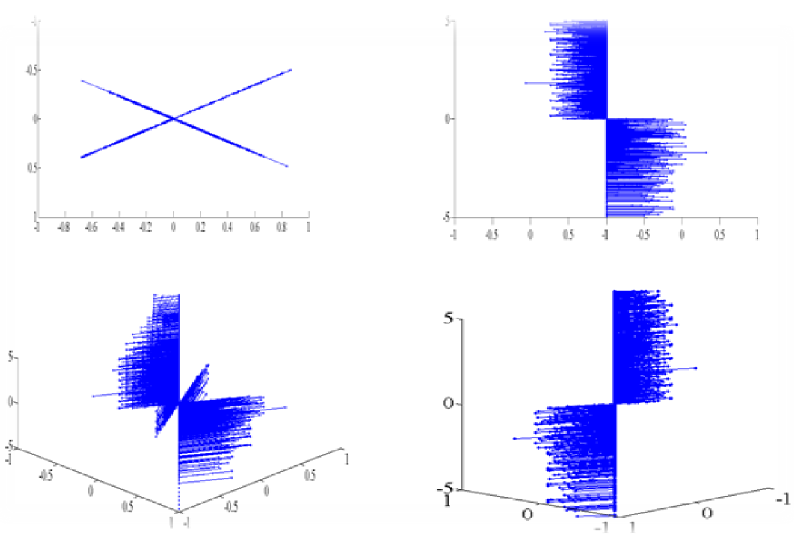

FIGURE 12: IDS irradiation pattern for SISO system with torque error as input and inverter vector as output

7. SIMULATION RESULT AND COMPARISON WITH CLASSIC METHODS

The result of torque control and rotor flux for both DTC based on IMC and the proposed method is presented in Fig.13-fig.16. Good dynamic behavior of torque responses when reference torque suddenly changes from 100Nm to -100Nm at time t=0.3 is shown. As can be seen, the ALM leads to less deviation from the desired value of torque and rotor flux (reference value) rather than the conventional DTC, this is due to its adaptability with motor model and the total system, also obviously switching frequency is decreased. According to the torque figures, ripple reduction of about 25% during using this method is created. Also by applying this method to the DTC, ripple rotor flux is reduced around 15%. Fig.17 and fig.18 show the flux response, flux circular trajectory and rotor flux sector. DC-link voltage of IMC is shown in Fig.19, Also Fig.20 and fig.21 show the 3-phase stator and rotor currents. These currents are sinusoidal and demonstrates that there are no low order harmonics.

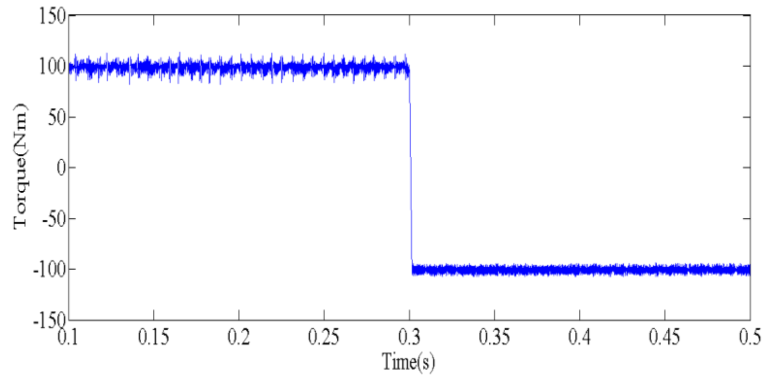

FIGURE 13: Output torque of DTC based on IMC

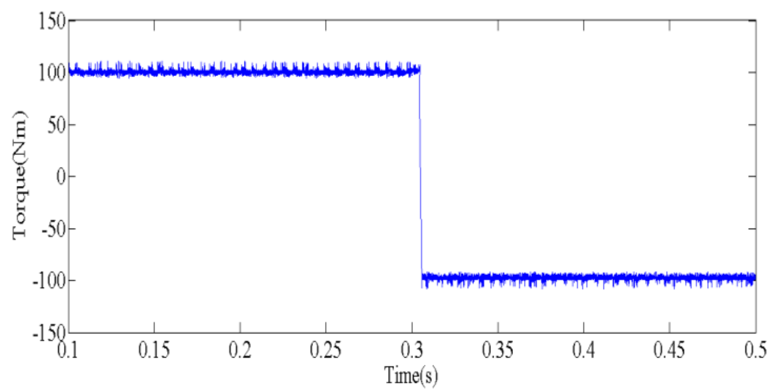

FIGURE 14: Output torque of enhanced DTC based on IMC by ALM

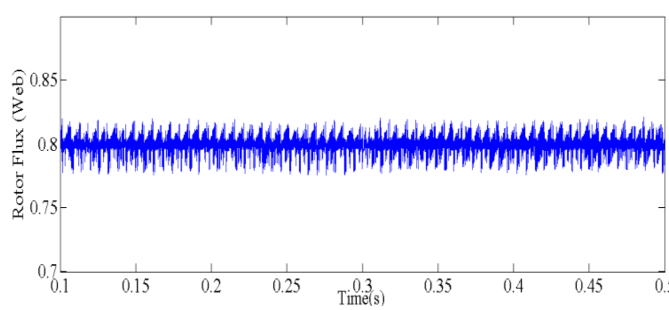

FIGURE 15: Flux response of DTC based on IMC

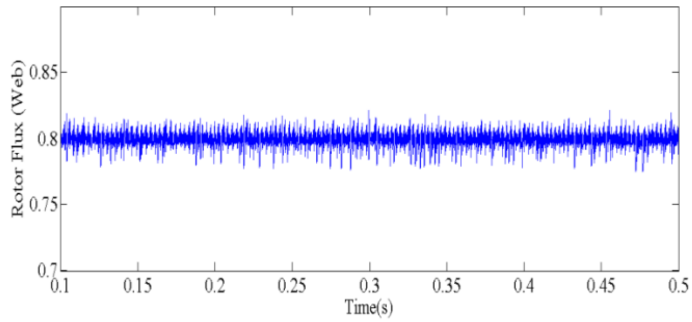

FIGURE 16: Flux response enhanced DTC based on IMC by ALM

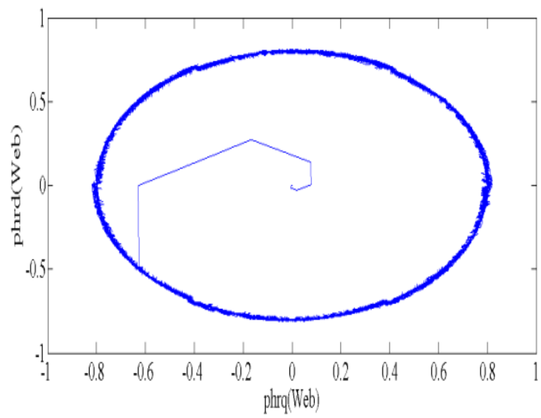

FIGURE 17: Flux circular trajectory

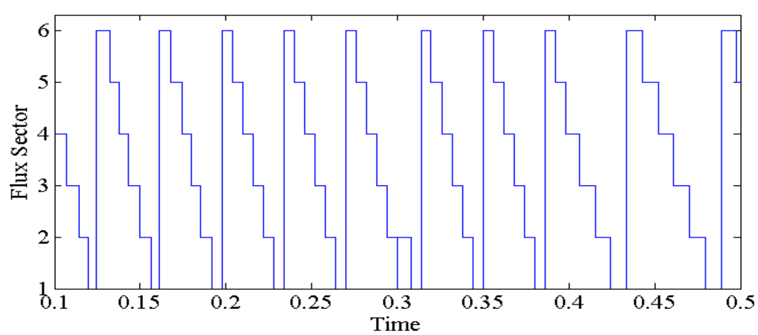

FIGURE 18: rotor flux sector

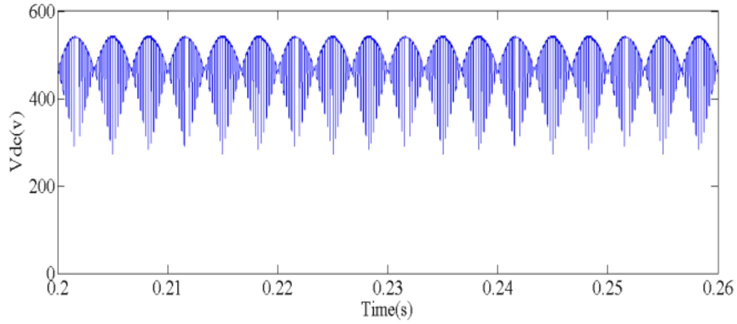

FIGURE 19: DC voltage of IMC

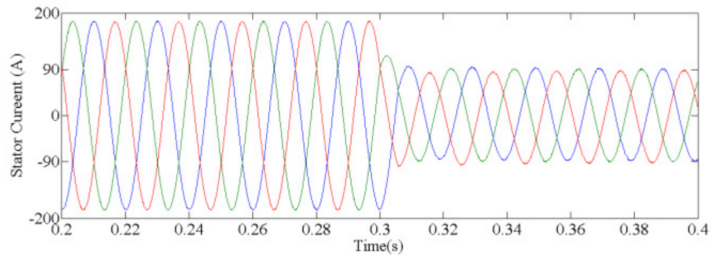

FIGURE 20: Three phase stator current

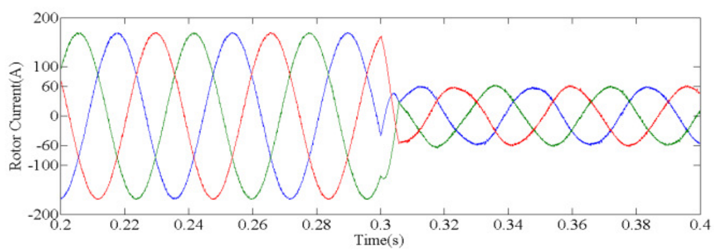

FIGURE 21: Three phase rotor current

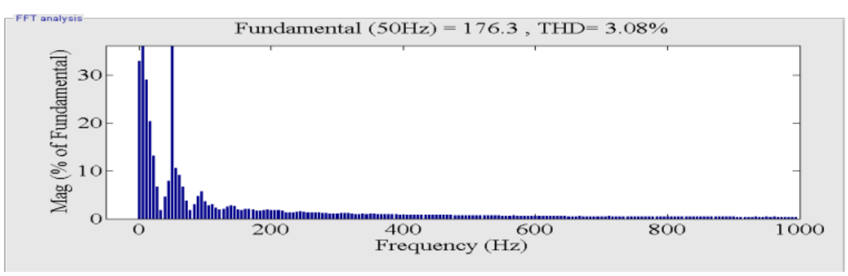

FIGURE 22: Current harmonic spectra of stator

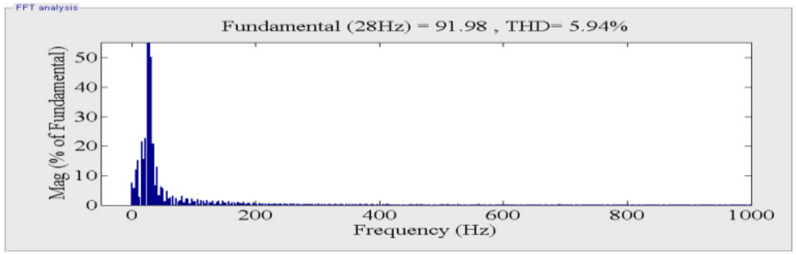

FIGURE 23: Current harmonic spectra of rotor

8. CONCLUSION

This paper tries to explore reducing of flux and torque ripple which are the inherent negative characteristics of DTC by an actively trial and error method called Active Learning Method for Doubly Fed Induction Machine based on Indirect Matrix Converter. Using DTC strategy with IMC result that the benefits of both method simultaneously obtained. The advantages are: fast response in torque control, regeneration capability, near sinusoidal stator and rotor current. Also usage of four-step commutation in rectifier stage of IMC which is the source of feeding the rotor is analysed to reduce the losses' caused by snubber circuit. In addition the concept Ink Drop Spread (IDS) is applied to handle different modeling target to predict on the data and get a behavior curve in DTC. Finally the simulation results confirm that a significant torque and stator flux ripple reduction are obtained.

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