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Quantization Noise Reduction Using Random Dither in Direct Torque Control of an Induction Motor

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ABSTRACT

A direct torque control (DTC) induction motor drive is presented in this paper. Quantization errors of current and voltage measurements are simulated and considered. To reduce the average quantization error and other offset errors of current and voltage measurement and eliminating the increasing integrator errors, a random dither signal is added to the truncating analog to digital converter (ADC) outputs. In this method, the ADC mean error is reduced to zero and therefore, integrator output error is mitigated. The proposed quantization method can improve the digital converter result; thus, this method can decrease the current measurement result. Thus, the torque and flux rippleswere be decreased. The proposed dither injection method can be used in Digital signal processor (DSP) or FPGA implemented applications. Experimental results show the performance of the proposed method.

Article Info

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Direct torque control, Dither Injection, Induction Motor Drive, Quantization

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I. INTRODUCTION

Digital control systems need ananalog to digital converter (ADC) to measure physical data. ADC operation can be modeled by two sub-processes called sampling and quantization [1-4]. The sampling operation incurs no loss of information as long as the input is band-limited in accordance with the sampling theorem [5]. But during quantization, truncating or rounding of the analog signal to a digital signal level, always result in signal degradation [5]. Also, offset error is important where the digital signal must be integrated. Integrating a signal with a small offset error causes the output error to increase linearly by time. In direct torque control (DTC) of an induction motor, estimation of the flux needs integration of the motor current [1,6,7]. Therefore, if a small offset error flaws in the current measurement then the flux estimation error will increase linearly.

The signal dithering is a method to overcome these errors; this method has many applications in digital audio and image processing [5,8]. In control systems, the dithering has not been used commonly as a method to reduce input noises, but it is used as a method by which high-frequency disturbances is introduced to a slow dynamic system to suppress problems like static friction and squeal [9-11]. In this paper, the dithering is used to reduce the mean error of measuring stator currents to zero and suppress the integration of the torque and the flux calculation errors. The DTC method controls both the stator flux and the electrical torque decupled without using any current feedback, PWM algorithm, or rotary coordinate conversion module. Therefore, compared with the field-oriented control method, the DTC technique has a

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simpler structure, faster torque response, and better robustness against parameters changes [12]. However, the basic switching-table-based DTC method has some outstanding drawbacks such as variable switching frequency due to the presence of the hysteresis controllers. Also, this method has high torque and flux ripples due to the low number of inverter switching states, and high sampling requirement [13-15].

A suitable look-up table for DTC of three-level dual voltage source inverter fed open-ended winding IM drive is proposed [15], where the VVs selection for lower hysteresis boundary conditions of torque and flux are restructured with null voltage states.

Two simple control methods with a fixed frequency are proposed for improving DTC of induction machines, which is named as CFTC-DTC in [16]. The CFTC-DTC was initially introduced to reduce torque ripple and achieve constant switching frequency in inverters. However, when compared to the original DTC, the CFTC-DTC algorithm suffers from slow torque dynamic response owing to the selection of zero-voltage vectors during torque transient [16].

A suitable duty cycle control technique to reduce torque,flux ripples, and harmonic loss in DTC of six-phase induction machine is proposed in [4]. Three different methods are proposed to improve the performance of DTC Switching Table of machine. The quantization noise cancellation method is used in other applications [17 and 18]. Using of the dither injection method can be used any application with ADC to decrease the error of digital converter. According to these technical points, the quantization noise reduction of the DTC of an induction motor is very important.

II. Direct Torque Control

In a two-level inverter, a DC voltage is inverted to a three-phase output, by means of two switches for each output phase. These six switches can be commanded in six different ways. For each value of the motor torque and the vector form of the stator flux, a suitable switching state can be selected to excite the motor to simultaneously control the flux and torque. This is the basic principle of the DTC scheme.

Figure (1) shows theDTC diagram. The torque and flux vectors must be estimated or calculated from measurable motor parameters. Estimated torque and flux are compared with their desired values and the error signals go to hysteresis blocks to determine the desired changes of the flux and torque. For torque error signal, the hysteresis block is a tree-level hysteresis block. But for flux error, it is a two-level block. Then the suitable switching states are determined by a switching table. Also, the appropriate switching states depend on the angle of the stator flux in the vector space.

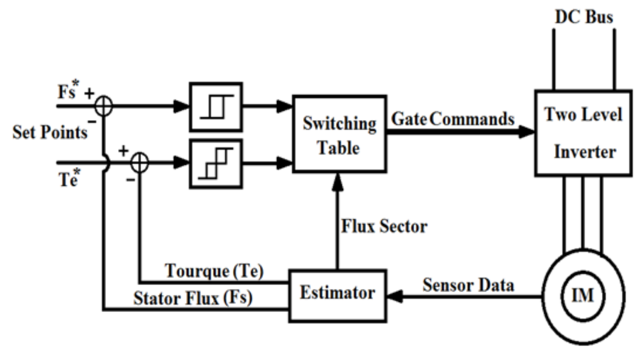


Fig. 1. Used DTC method diagram

If the vector space is divided into six different sectors, as shown in figure (2), each sector has its own suitable switching states depending on the hysteresis block outputs.

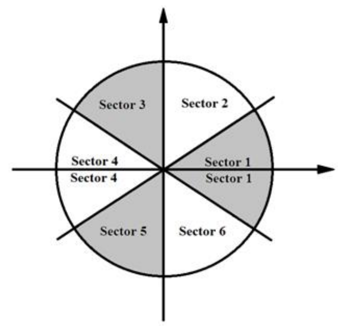


Fig. 2. Two-level inverter switching vectors and stator flux sector

Table (1) shows a switching table for a two-level inverter DTC system. In this way, the torque and flux of the induction motor can remain with a suitable hysteresis band around their desired values, and therefore can be controlled directly by changing the switches.

TABLE I
DTC SWITCHING TABLE

		Sector					
Flux	Torque	1	2	3	4	5	6
Increase	Increase	V2	V3	V4	V5	V6	V1
	No Change	V0	V7	V0	V7	V0	V7
	Decrease	V6	V1	V2	V3	V4	V5
Decrease	Increase	V3	V4	V5	V6	V1	V2
	No Change	V7	V0	V7	V0	V7	V0
	Decrease	V5	V6	V1	V2	V3	V4

III. Quantization and Offset Errors

The process of converting an analog signal to a digital value in ADCs consists of two stages; one is the sampling, and the other is the quantization (figure 3). During the sampling stage, the input analog signal periodically is held to give enough time to the next stage to measure and convert the analog signal. During the quantization stage, the held analog signal is truncated or rounded to a digital neighbor level and then converted to a binary digital number.

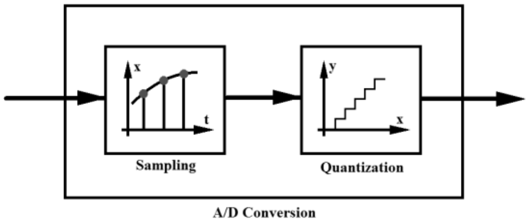


Fig. 3. The quantization model

An ideal ADC uses arounding method; therefore, the mean output error will be zero. If the ADC uses thetruncation method, a mean offset error of value 1/2LSB, will be added to the actual mean value of the original signal. Today many ADCs use therounding method to eliminate this offset error because if this digitized signal needs to be integrated, this small offset error will produce serious problems.

Earlier airplanes with mechanical computers were working more accurately, during fly, because of high-frequency vibrations. This high-frequency vibration was called dither [12]. After that, dither as a technique found many applications in mechanical and electromechanical systems and digital signal processing [5]. In the mechanical and the electromechanical systems, dither means superposition of high-frequency vibration to stabilize a low-frequency vibration [10]. Suppressing squeal in car wiper system [10] or brake system, [11], are two examples of these applications. However, in digital signal processing, it has a little different meaning. In this area, dithering is an intentionally applied form of noise to reduce quantization errors [5].

IV. DTC Simulation

The DTC of an induction motor is simulated in MATLAB Simulink. In this simulation, the induction motor is modeled in d-q coordinate system. A simple PID controller measures the motor speed and determines a suitable torque set point for the DTC measures the motor currents and voltages and estimates its torque and flux vectors. Then, the appropriate switching state is calculated to keep the motor torque and flux in their determined boundaries. Figure (4) shows the Simulink block diagram of this simulation. The motor fluxes magnitude is shown in figure 5(a). As we see, the flux is controlled around its desired value. As mentioned in previous sections, the DTC will control the stator flux vector to rotate around a circle in d-q coordinate system. This circular stator flux graph is shown in figure 5(b). The motor torque is controlled around the load torque to overcome the load torque. The motor Torque is shown in figure 6(a). The desired suitable PID controller controls the speed of the motor shaft by determining suitable torque setpoints. The motor speed is shown in figure 6(b). Compared with the motor frequency response, the DTC outputs are high-frequency switching signals applied to power electronics switches. Therefore, the voltages applied to three-phase motor inputs have high-frequency pulsating voltages. Because of the low-frequency response of the motor, the average power of these pulsating voltages determines the motor response.

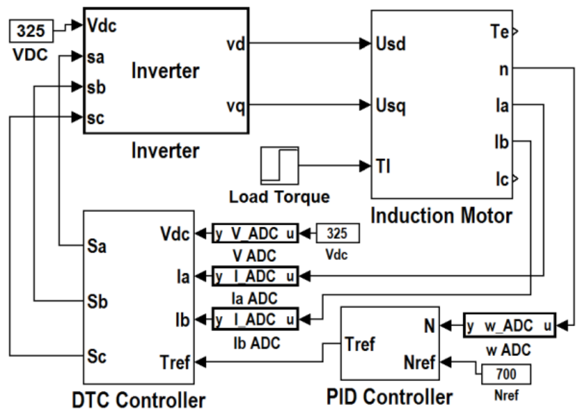


Fig. 4. DTC system simulation in MATLAB Simulink

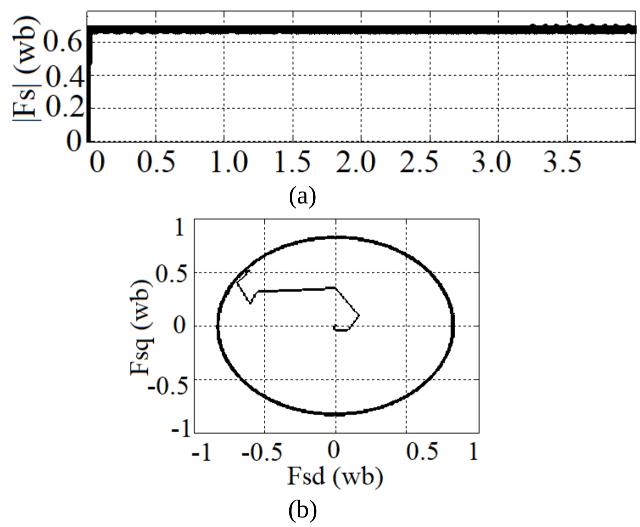
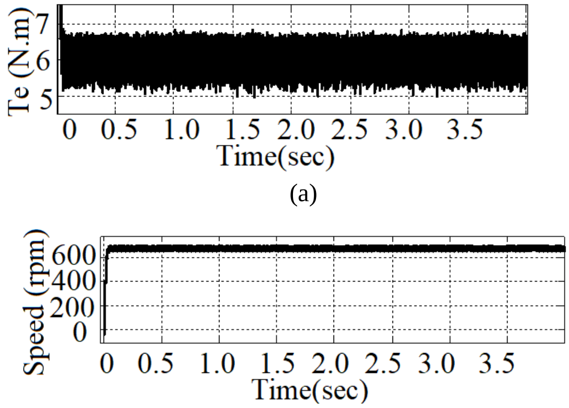


Fig. 5. (a) Stator flux magnitude, (b) Stator flux vector in d-q coordinate

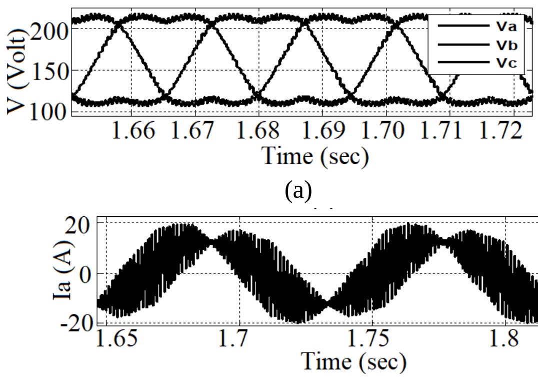
In figure 7(a), averaged voltages are shown. This figure shows that the averaged voltages which are applied to the motor are three phase sinusoidal voltages. The motor current in phase (a) is shown in figure 7 (b). In the experimental setup, two phases of these currents are measured with ADCs and the third phase current is calculated.



(a)

(b)

Fig. 6. (a) Electromagnetic torque, (b) Motor speed



(a)

(b)

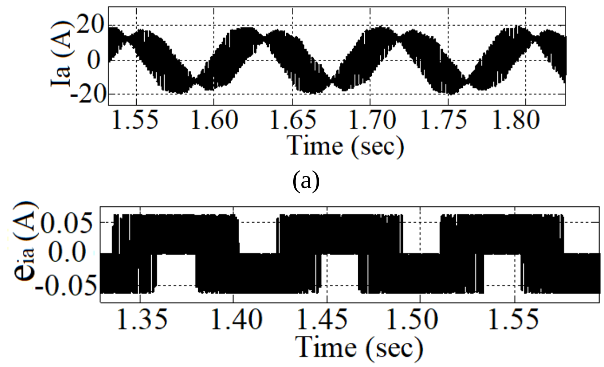
Fig. 7. (a) Averaged motor voltage, (b) current phase.

V. SIMULATION OF THE QUANTIZATION ERROR

To consider ADC error, small ADC blocks designed in the model. To model ADC, firstly, the transfer function of an ideal ADC [5] is used. In theused DTC system, the controller measures the currents of two phases of the motor using hall effect sensors, and then the third phase current is calculated using these two measurements.

Therefore two current sensors are sufficient for this controller. Figure 8(a) shows the current measurement of phase a, using this ideal ADC that uses arounding method for the quantization. Since three-phase currents are dependent on each other, Ia and Ib are measured by two ADCs and Ic is calculated. The quantization error of measurement Ia is shown in figure 8(b). As it is shown in this figures, the average quantization error of ideal ADCs over a sufficient period of time will be zero.

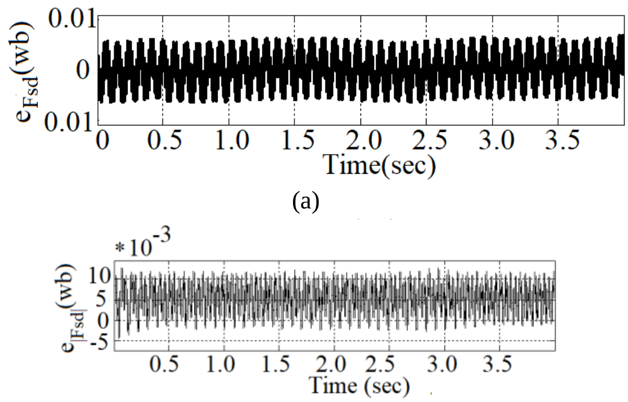
Zero average ADC errors help the integration carried out properly. Also, integrator blocks do not increase errors. The resulting motor direct component (d-axis) of flux estimation error, and the total flux magnitude error, using ideal ADC models are shown in figures 9 (a) and (b), respectively.



(a)

(b)

Fig. 8. (a) Phase a current, (b) Ia measurement error, (Ideal ADC)



(a)

(b)

Fig. 9. (a) Fsd estimation error, (b) |Fs| estimation error, (Ideal ADC)

These flux errors are small enough and do not increase with time. Therefore, the motor flux is estimated in a suitable range around its actual value.

VI. SIMULATING WITH OFFSET ERRORS

Although manyof today's ADCs removed truncation offset errors, they still have other sources of offset errors. These offset errors are calculated during thefabrication process, and they are mentioned in the ADC datasheets. Therefore compensating these offset errors is a problem when long interval integrations are carried out. To model ADCs with thetruncation method, a constant offset is added to the ideal ADC model prepared in the previous section. This way the truncating ADC offset error is simulated by setting the offset equal to 0.5 LSB. Also, other offset errors can be simulated by changing this value. Measured phase a current is shown in figure10 (a). As mentioned above,the mean quantization error is not zero in this case. The average quantization error for this ADC has a negative value as shown in figure 10 (b).

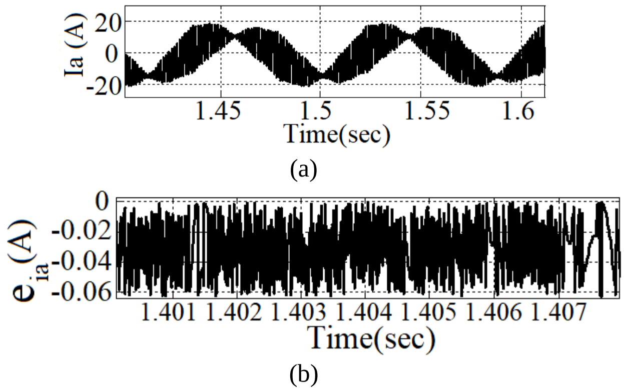


Fig. 10. (a) Phase a current, (b) Ia measurement error, (non-Ideal ADC)

According to figure 11 (a), the current measurement errors resulted inincreasing errors in the direct flux component. Figure 11(b) shows theincreasing fluctuation in the flux magnitude. As it is shown in figure 12 (a), the actual flux magnitude has gone away from its estimated value; and it is not close to the estimated flux magnitude. The circular graph of the actual stator flux vector is shown in figure 12 (b). According to that, the controller controls its estimated flux around its desired values, but the actual flux goes away from its desired value, as the error increases.

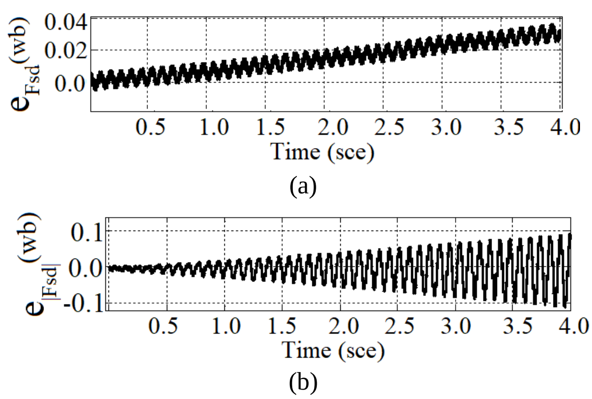


Fig. 11. (a) Fsd estimation error, (b) |Fs| estimation error, (non-ideal ADC)

In d-q coordinate system, the increasing error appears as a shift of circular flux graph with respect to the estimated circular flux graph. In figure 12 (b), the actual and estimated fluxes are shown. The estimated flux vector (red) rotates properly around a circle, but the actual flux shifts in a direction which is shown by the black arrow.

VII. DITTER INJECTION

To eliminate the current measurement offset error, we cannot add a constant to the ADC output. Because the ADC offset error is 0.5 LSB and this error will be vital if it is integrated.

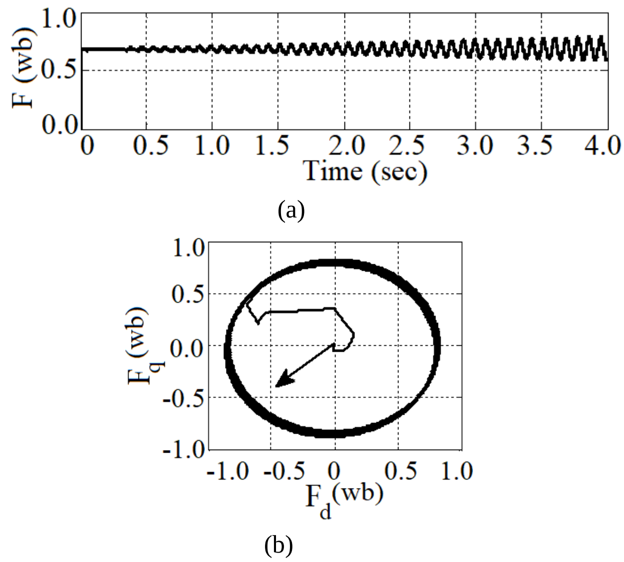


Fig. 12. Non-ideal ADC, (a) Actual stator flux magnitude, (b) Flux vectors in d-q axis

To resolve this problem, a random one-bit signal is added to the ADC output.

The mean value of this random signal eliminates the mean offset error of the ADC. The resulting measured phase a current is shown in figure 13 (a). Quantization errors, in this case, are similar to the previous section. Figures 13 (b) shows the phase a current quantization error.

A random dither signal is added to the ADC output to zero the mean ADC error, which was smaller than one bit in our digital control system. The current measurement error after dither injection is shown in figure 13 (c).

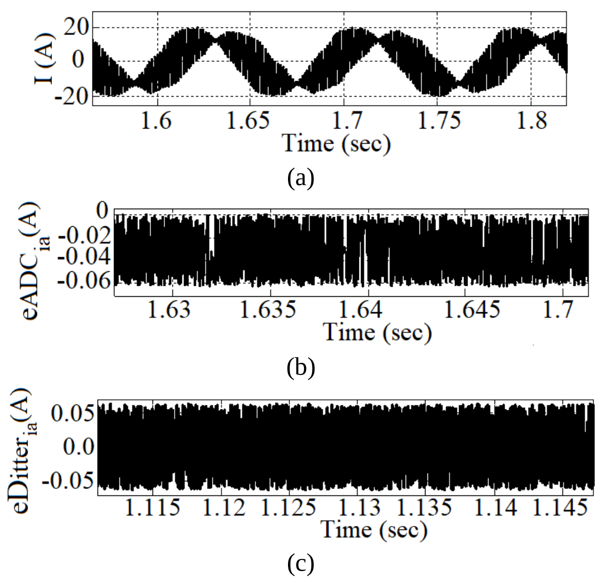
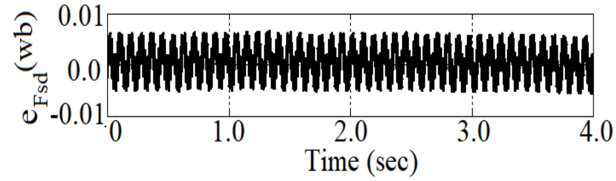
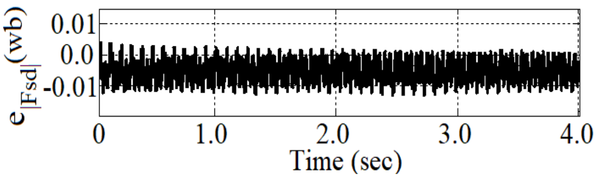


Fig. 13. Ditter injection results, (a) Phase A current, (b) Ia measurement error, (c) Ia measurement error



(a)

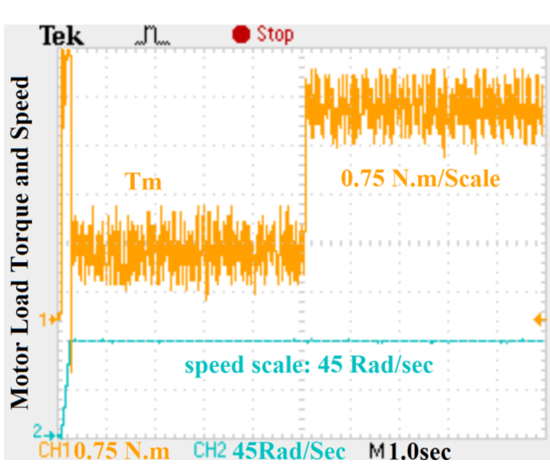


(b)

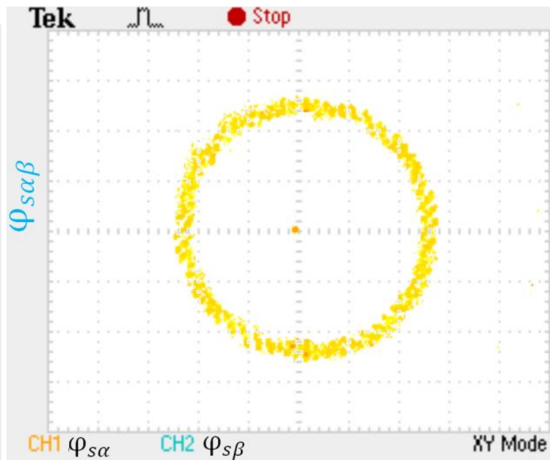
Fig. 14. Ditter injection results in flux estimation, (a) Fsd estimation error, (b) |Fs| estimation error

As it is shown, adding dither changed the mean error back to zero. Again, by decreasing the mean errors to zero, the increasing flux estimation errors are disappeared. The resulting motor direct component of flux estimation error, and the total flux magnitude error, using dither injection are shown in figures 14 (a) and (b), respectively.

Experimental results were added to the manuscript. The experimental results are shown below. The proposed methods is developed and tested in the experimentalsetup. The proposed techniques in DTC of IM are implemented on a Tms320f28337 board. Experimental results of the proposed techniques in DTC IM are shown in Figure.15. Figure 15 shows experimental results of load torque, motor speed, stator flux of d axis according to q axis, phase current, and flux amplitude.



(a)



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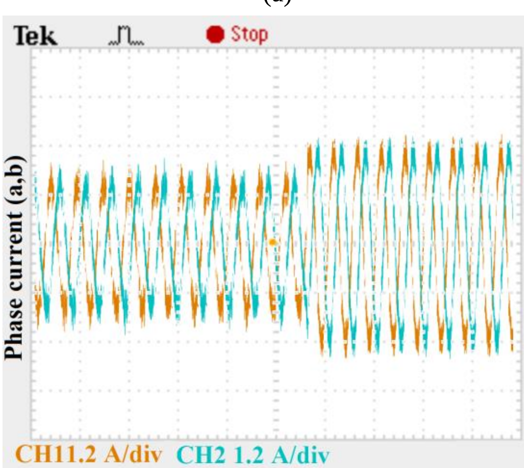

(c)

(d)

Figure 15 . Experimental results of DTC method, a) motor load torque and speed, b) stator flux of d axis according to q axis, c) phase current, and d) flux amplitude

VIII. CONCLUSION

A random digital dither signal is used to reduce the mean offset error of the motor current measurement to zero. Simulation results show that the increasing integration errors eliminated, and the motor torque and flux controlled properly as the case where an ideal ADC without offset errors is used. According to results, theproposed method decreases the ADC error in DTC of induction motor and improve motor performance.

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