EXPERIMENTAL TESTING AND EVALUATION OF VIBRATIONS IN VARIABLE SPEED SWITCHED RELUCTANCE MOTOR FOR ELECTRIC VEHICLES

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Abstract: *This paper describes the vibration analysis of DSP based sensorless Switched Reluctance Motor drive used for Electric vehicles (EVs). The vibration of the motor is measured with help of National instrument (NI) vibration sensor suite under different load conditions. A higher order time domain analysis and FFT spectrum of measured vibration signals are also presented. To demonstrate the effectiveness of the randomized turn off angle generation in sensorless control, the vibration, torque and speed results are compared and analyzed with conventional Proportional-Integral (PI) controller with constant turn off angle control. The algorithm has been implemented using TMS320F2812 DSP controller and tested with 1 hp,8/6 SR motor. A experimental results prove that the proposed randomized turn off angle method increases the performance of sensorless control system in terms of less speed oscillation, less torque ripples and less vibration even low speed in steady state condition than the constant off angle methods.*

Key words: *SRM drive, PI controller, vibrations, neural network, Sensorless control*

1. INTRODUCTION

In Industrial automation applications need variable speed operation for reducing energy consumption and produce the quality product with minimum cost. The electric drives is the perfect choice for variable speed operation, now days the research in electrical drives is focused towards implementing energy efficient and robust motors in variable speed drive applications. SRM have the simplest and rugged construction among all electric motors and it has various industrial applications [1-3]. Although SRM have many advantages, it has certain limitations such as high torque ripples, high acoustic noise and vibration. The design procedures of the SR machines and its operating characteristics have been reported in the literature [4-6]. However, due to the double-salient construction and nonlinear inductance, torque production is highly nonlinear. Due to this reason SRM speed control system is more complex one. The correct excitation of phases with rotor position is need for vibration and acoustic noise less operation. The position sensor system will support for phase synchronism. However, for some applications, this position sensor system not suitable due to high cost, size, weight, environmental factors and its reliability. A development of sensorless speed control operation of SRM will be the solution for the above problem.

In general, a traditional control schemes, like Proportional Integral (PI) control is used for designing a controller to construct SRM drives. The speed control techniques for SRM drives have been reported in the literature over the last few years. For the sonsorless operation, predetermination of rotor position or speed parameters is play vital role for good performance of the SRM drives. A different strategy for sensorless control of SRM drives have been reported in the literature, it was based on dynamic adaptive commutation tuning scheme and etc.[7-10] . Artificial intelligent based rotor position prediction system such as fuzzy logic, neural network, neuro-fuzzy has been developed [11-13]. Hudson et al.[14] have developed neural network based position estimation system using the phase current and flux parameter and it has been tested with three phase SRM drive and It requires minimum arithmetic operation for real time implementation in a floating point processer.

Research regarding vibration and acoustic noise problem generation, analysis and reduction in SR motor has been investigated and their findings are reported in the literature work [15-19]. As per the previous literature work the acoustic noise can be classified as magnetic, mechanical, aerodynamic and electronic and it was found that the vibration measurement gives better results than acoustic noise measurement system. Normally the vibration reduction in SR motor has been achieved through optimum motor design, converter control methods. The random turn on and off angle tuning have used to control the vibration in SR motor [20]. This method gives better results and also there is no much complex procedure to implement. A hybrid excitation method was developed [21] based on overlap excitation concept. Ha et al.,[22] have proposed new vibration and noise reduction method based on transfer function and response surface methodology. In [23] comprehensive experimental analysis has done in order to compare the vibration and noise reduction methods. In his research work proposed new reduction methods it includes RFPWM with robust harmonic spectrum shaping, advanced turn-on and turn-off, randomising turn-off angle and etc. In the above all the works deals about the system having with sensor control operation. In sensorless control operation the SRM drives behave in different manner than sensor control operation. only limtated work was found in the literature for dealing the vibration in sensorless variable speed SRM drives. In [24] new methods for reduced acoustic noise in sesorless SR drive have developed based on variable DC bus voltage. In this method the noise level is reduced to 15db compared to other scheme in low speed operation but this scheme required quality power supply.

There are many existing vibration and noise control scheme for sensor drive, but in sensorless drive only limited schemes are available. The measurement systems need to be updated one for current advancement. A detailed vibration analysis are required for sensorless SR drive operating in steady state mode in the HVAC applications. Based on the above requirements this paper discussed about the advanced instrument based vibration measuring and its analysis for DSP based sensorless variable speed SR drive under steady state. NN based sensorless control was already tested in simulation and experimentally in the previous research [25]. In this paper, NI based vibration measurement suit was used to measure the vibrations of the motor at different conditions. One of the vibration reduction method, turn -off angle randomisation has been implemented and its performance was compared with constant turn-off angle excitation.

2. SWITCHED RELUCTANCE MOTOR

A Switched Reluctance Motors does not contain any permanent magnets. The stator is similar to a brushless dc motor. However, the rotor consists only of iron laminates. The iron rotor is attracted to the energized stator pole. The polarity of the stator pole does not matter. Torque is produced as a result of the attraction between the electromagnet and the iron rotor. Fig.1 shows the cross section of typical 4 phase (8/6) SRM.

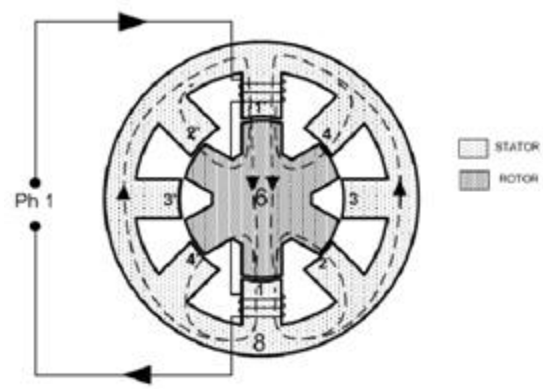


Fig.1. Cross-sectional view of 4 Phase SRM

The mathematical model of SR motor can be modelled as follows:

$$v_k = R_k i_k + \frac{d\psi_k(\theta_r, i_k)}{dt} \qquad k = 1,2,3,4 \qquad (1)$$

Where v_k is the stator phase voltage, R_k is the stator phase resistance; i_k is the stator current, ψ_k is the stator phase flux linkage and θ_r is the rotor positon.

The stator flux linkage can be expressed without mutual phase to phase inductance as

$$\psi_k(\theta_r, i_k) = L_{kk}(\theta_r, i_k) \times i_k \qquad k = 1,2,3,4 \qquad (2)$$

Where $L_{kk}(\theta_r, i_k)$ is the per phase self-inductance.

The electromagnetic torque can be represented as

$$T_e = \frac{1}{2}\frac{dL_k}{d\theta} {i_k}^2 \qquad (3)$$

The mechanical equation of the SRM is

$$T_e = J_m \omega_r + B_m \omega_r + T_L \qquad (4)$$

Where J_m the moment of inertia is, B_m is the viscous frictional coefficient, ω_r is the rotor speed and T_L is the load torque.

based on the observation made in (Cai et al.,2001) large torque ripples and notch between adjacent phase are presented in the torque waveform due to its non ideal current wave.

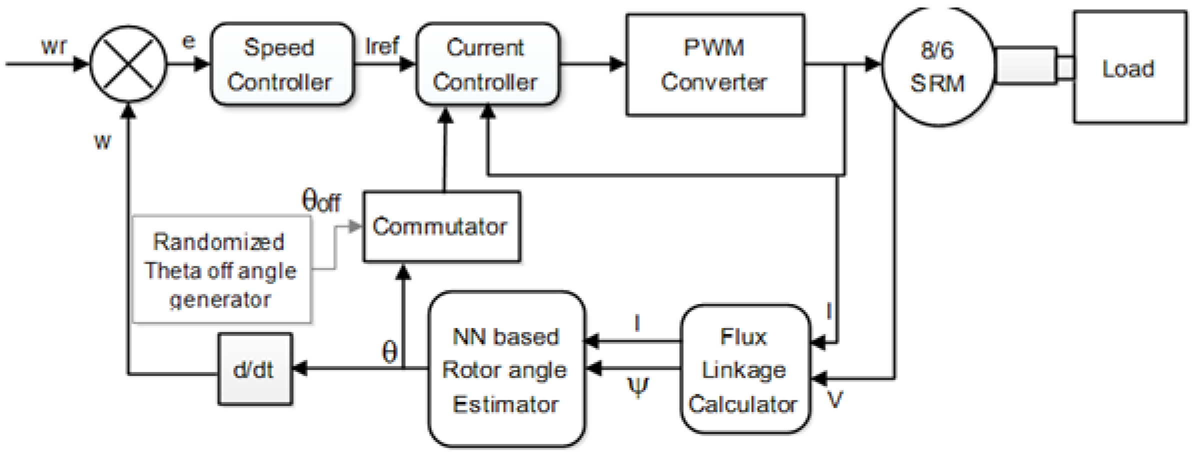


Fig. 2. Control configuration of an SRM drive

Fig. 2 shows the proposed control system of an SRM drive. The control system consists of SRM with eddy current load, a current regulator device, a commutator, a speed controller, flux linkage calculator, minimal-NN based rotor angle estimator, randomized turn off angle generator and voltage and current sensors. The current reference is processed by the current controller based on the current reference the duty cycle signals to be given to PWM convertors. The flux linkage is calculated using mathematical equations and the rotor angle is estimated by minimal-NN based on input current and calculated flux linkage values. Commutator process and generates the switching angle based on the estimated rotor position. The speed error is processed by speed controller to generate the reference current signals to current controller. The above control system has been tested successfully in the previous research work [25].

3. SOURCE Of VIBRATION AND NOISE

The noise sources for SR motor are discussed in the literature work. Normally due to the rate of demagnetization stator vibration has been produced, due to normal control algorithm torque ripple generated, it is the main source for noise, interaction between the currents in the stator windings produce vibration, under magnetic effect the noise will produce, bearing faults and other mechanical faults will leads to vibrations. the vibration and noise reduce in SR motor by proper design of motor and development of appropriate control algorithm. In this work randomized Turn off angel method is used to reduce the vibrations in SRM.

4. RANDOMIZED TURN OFF ANGLE METHOD

The randomized turn-on and turn-off angles to reduce the torque ripples, noise and speed oscillations have been reported in (Boukhobza,2001) . Though the turn off angle is the important variable relating to the operation of the drive, only the randomized values are considered.

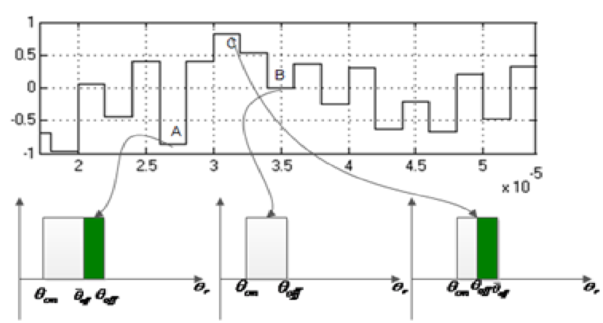


Fig.3. Random turn-off angle generation

The random turn-off angle tuning is shown in Fig. 3. The turn- on angle is fixed and turn-off angle is randomly varied around the average value based on the below equation

$$\bar{\theta}_{off} = \theta_{off} + y(t)\Delta\theta \qquad (5)$$

Where θ_{off} is the original turn off angle, $\bar{\theta}_{off}$ is the varied turn-off angle , $\Delta\theta$ is the magnitude of turn-off angle variation and $y(t)$ is the uniformly distributed random numbers between [-1 to +1]. The equivalent overlap angle is reduced as the results of randomizing turn-off angle. It will minimize the torque ripples considerably.

5. EXPERIMENTAL TEST SETUP

A 1 HP, 4 phase, 8/6 SR motor has been used in this work. The structure of the motor is shown in fig.1. the specification of motor is given in Table 1. The SR motor has been coupled with DC separately exited motor for provided resistive based loading. A SRMpower module is used to drive the motor. A spilt phase power converter, diode rectifier, Hall effect current and voltage sensor, over current and temperature protection circuit and input output ports are embedded in a single unit as SRMPower module. A incremental encoder is used to sense the rotor position for initial starting of the motor and verity the estimated rotor positon. A TMS320F2812 DSP controller is used to implement the proposed control algorithm. It is 16 bit fixed point with ADC conversion speed 80ns. It has 16 ch high frequency PWM ports. A 3GB RAM,2GHz intel processor PC is used to develop the coding. The estimated rotor positon feed into the DSP controller in QEP1 pin. The block diagram of the complete drive system is shown in Fig.2. The photograph of the experimental test setup is shown Fig.4.

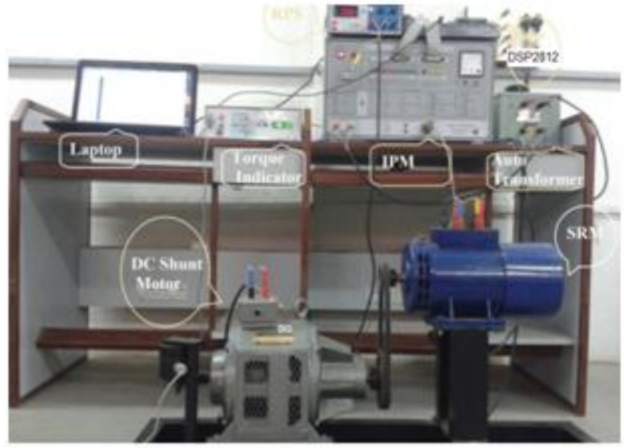


Fig. 4. photograph of Experimental test setup

Table 1. Specifications of SRM

Phase	4
Stator pole number	8
Rotor pole number	6
Rated voltage	230V
Rated current	10A
Rated speed	4000 rpm
Rated load	0.75 kw
Moment of inertia(Jm)	0.005 kg-m^3
Viscous friction coefficient(Bm)	0.005 Nm/(rad/s)
Stator resistance (R_k)	50 m-ohm

5.1 Implementation of randomised turn-off angle method

The software coding has been written in embedded C language using code composer studio. It has been developed for operating motor in closed loop current control and speed control. The Fig.5 shows the flowchart for randomised turn-off angle based PI controller implementation process.

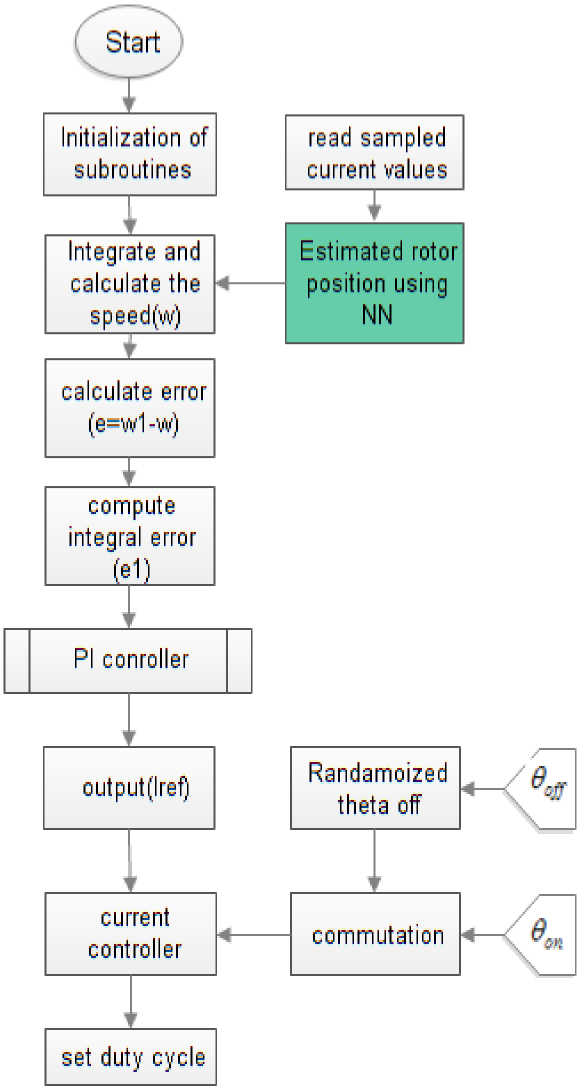


Fig.5. Implementation process of Randamoised Turn-off angle with PI controller for SRM

There are two control loops in the coding. First one is inner current loop, which runs at 47.5µs, regulates the phase current according to the reference current. The second one is outer speed loop, which runs at 22.5 µs, read the estimated rotor positon and calculated the actual speed. The speed error and integral of speed error are calculated then call the PI controller subroutine and gives the reference phase current. Initially the Turn On angle(Θ_{on}) Turn off angle (Θ_{off}) fixed as constant value later the turn off angle has randomised by 4^o .

5.2 *Advanced vibration measurement system*

A NI Vibration Sensor Suite is used to measure the vibration signals on the stator [26]. Suite consists of Triaxial accelerometer with sensitivity of 5-100 mV/g and DAQ card. The sensor is mounted on the stator surface and the PCB low noise coaxial cable is used to connect the DAQ. Finally the DAQ is connected with PC through USB connector. The LabVIEW programme has been written to extract the vibration signals for different conditions. The photograph of the measurement setup is shown in Fig.6.

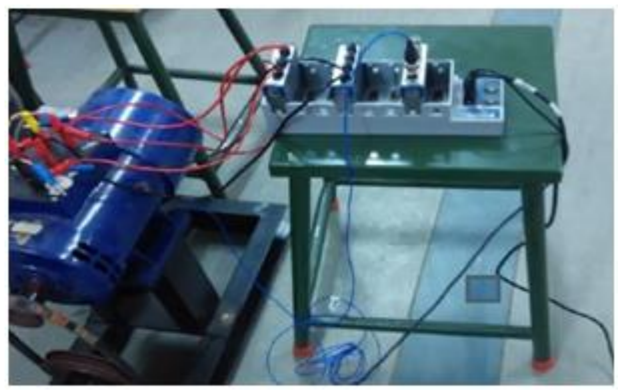
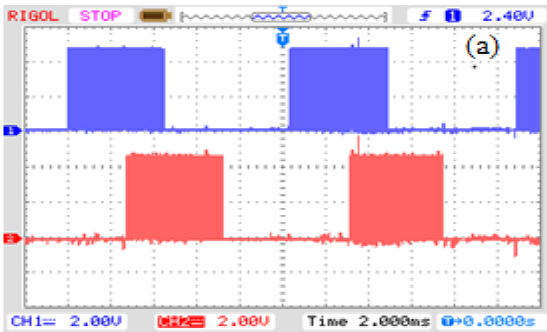


Fig. 6. photograph of advanced vibrations measurement setup

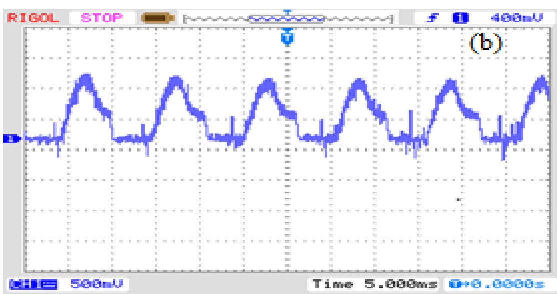
6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Speed and torque waveform

To check the vibration and noise level at different conditions of SR motor with constant Turn off angle and randamoised turn off angle are tested by experimentally in a 4 phase SRM drive system using PI control algorithm and the results are compared to demonstrate the performance of the proposed method. The following experimental testes were carried out. Fist the drive was operated from 500 to 2000 rpm with external constant load T_L=0.3 Nm(consider as no load) and T_L=1.5 Nm(75% of Laod) to verify steady state vibration and noise level of motor for variable speeds. Second, drive was operated at 1000 rpm with external variable load 0 to 75% to verify steady state vibration and noise level of motor for variable loads. The controller parameters of the conventional PI controller were obtained with Cohen and Coon (CC) controller tuning method. The DSO based measured PWM pulses and phase current for one phase are shown fig.7. The pulse and current profile of constant and randomised turn off angle methods are measured using NI DAQ, which is shown fig8. The shape of the current wave form is improved for randomised turn off angle method.



(a) PWM pulse to IGBT switch



(b) Phase current at A phase

Fig. 7. The gate pulse and current wave form at no load

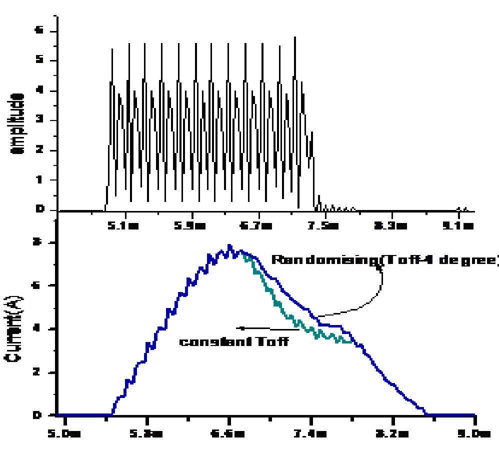


Fig. 8. The gate pulse and current wave form at 75% of load

The speed oscillation for constant and randomised turn off angle at reference speed 1000 rpm at no load and 75% load at 1000rpm conditions is shown in Fig. 9 The speed responses clearly demonstrate that the randomised turn off angle method makes the drive to run constant speed with less oscillation than constant angle method. the speed variations is 15 rpm in constant Toff angle method and 5 rpm in randomized Toff method.

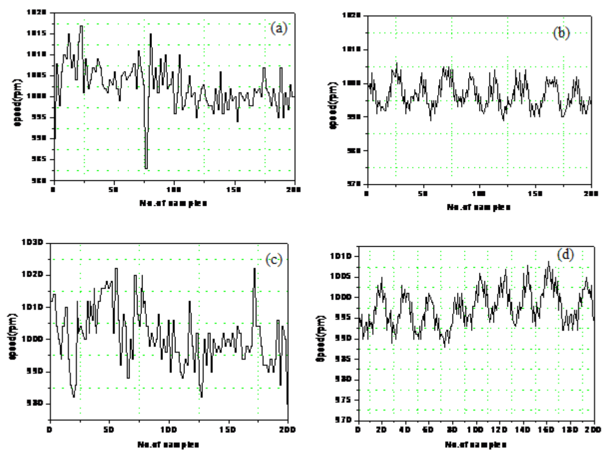


Fig. 9. Steady-state measured speed at no load and 75% load (a)(c) constant Toff (b)(d) randomized Toff

Fig. 10 shows the experimental torque response for the SRM drive under no load conditions at 1000rpm speed and variable load at 1000 rpm conditions. At PI based speed controller with constant Toff angle case more torque ripples are presented as shown in fig10(a) the maxim ripple magnitude is 1.5 Nm. and the number of the peak occurrence is 18 for 800 samples. At PI-randomized Turn off angle method less torque ripples are presented as shown in Fig10(b) the maxim torque ripple magnitude is 0.8 Nm and the number of the peak(notch between adjacent phase) occurrence is 10 for 800 samples. At PI based speed controller with constant Toff case more torque ripples are presented as shown in fig10(c) the maxim ripple magnitude is 1.8 Nm. and the number of the peak occurrence is 28 for 800 samples. At PI-randomized Turn off angle method less torque ripples are presented as shown in Fig10(d) the maxim torque ripple magnitude is 1.5 Nm and the number of the peak(notch between adjacent phase) occurrence is 13 for 800 samples.

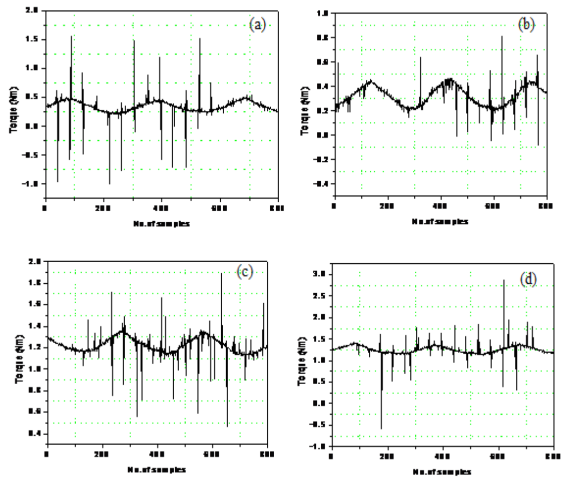


Fig. 10. Steady-state measured torque at no load and 75% load (a)(c) constant Toff (b)(d) randomized Toff

7. VIBRATION RESULTS AND ANALYSIS

The measured raw vibrations signals of SRM under different speed at constant load and different load at constant speed are shown in fig11 and fig 12 respectively.

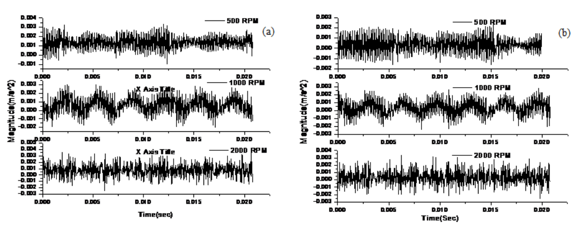


Fig.11 Measured vibrations under different speed conditions at constant load motor

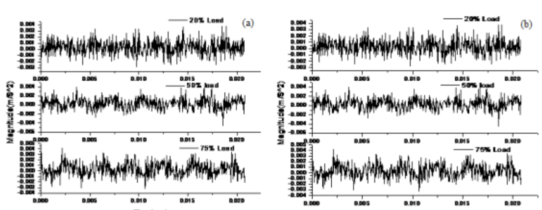


Fig.12 Measured vibrations under different load conditions at 1000 rpm

The Time domain statistics analysis such as standard deviation, peak, skewness and kurtosis are calculated for the measured vibrations signals and reported in the fig 13 and 14.

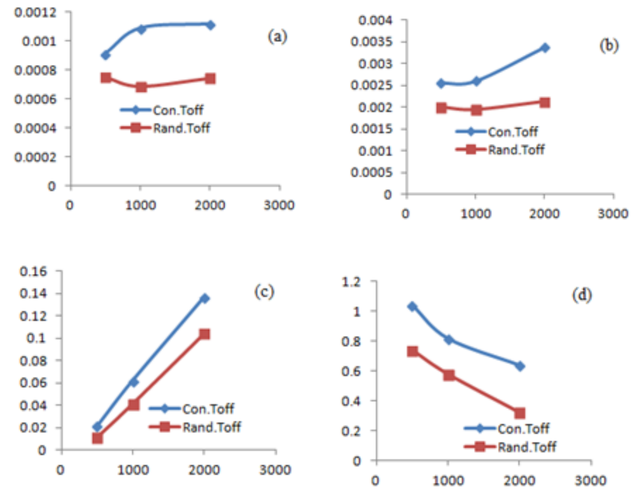


Fig.13 Time domain statistical value of vibrations signals under variable speed conditions(a) standard deviations (b)peak (c) skewness (d) kurtosis

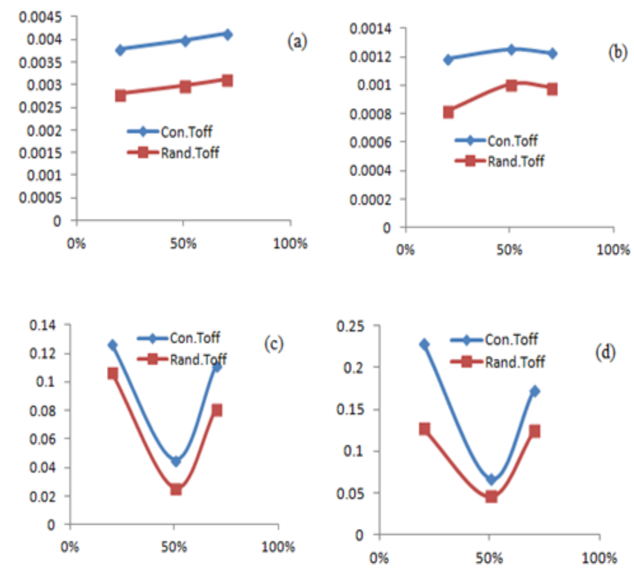


Fig.14 Time domain statistical value of vibrations signals under variable load conditions (a) standard deviations (b)peak (c) skewness (d) kurtosis

It is observed that the randomized Toff angle based method can reduce the vibrations of the motor under variable speed and load conditions. skewness values are positive, it shows that small and large amplitude of acceleration after 50% load the values are increased and while increase the speed it will reduce. In both case the kurthosis is less than 3, So vibrations have flat peaks only.

8 FFT SPECTRUM ANALYSIS

The frequency spectrum of the measured vibrations signals has been calculated and its spectrum is shown in figure 15. In variable speed operation with constant load a 36Hz, 3.2 kHz and 11.6kHz frequency vibrations are presented at constant Toff angle method but in randomized Toff method does not have these frequency vibrations.

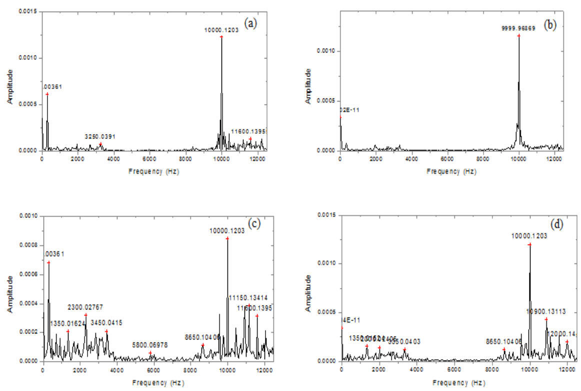


Fig.15 Frequency spectrum of vibration signals at no load and 75% load (a)(c) constant Toff angle (b)(d) randomized Toff angle

In variable load operation with constant speed a 36Hz, 1.3 kHz,2.3kHz, 3.4kHz,5.4kHz and 11.6kHz frequency vibrations are presented at constant Toff angle method but in randomized Toff method have 8.6kHz,10.9kHz and 12 kHz frequency with less amplitude are presented.

9. CONCLUSION

This paper proposed a PI controller with randomized Turn off angel method for speed control and advance instrument based vibrations measurement system for DSP based sensorless variable speed SRM drive. The vibrations signals and its higher order time domain statistical index and FFT frequency spectrum are reported under different speed and load conditions. Experimental test are carried out in 8/6 SRM drive system. The experimental results proved that the proposed speed controller maintains the motor speed at set speed with very minimum speed oscillations, torque ripples and vibrations. The randomized turn off angle method reduce the radial force during turn off so it will reduce the vibration effectively.

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