EXPERIMENTAL STUDY OF VIBRATION IN SRM DRIVE FOR ELECTRIC VEHICLE APPLICATIONS

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Abstract: *This paper describes the vibration analysis of DSP based sensorless SRM drive used for Electric vehicles (EVs). The vibration signals of the motor are measured using National instrument (NI) vibration sensor to 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 reported and comparative analysis between constant and variable turn off angle control are given. The algorithm has been implemented in real time by using TMS320F2812 DSP controller and tested with different experimental conditions on 1 hp,8/6 SRM drive. A test results are proving that the 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, Electrical vehicle, Sensorless control, noise, torque ripples*

1. Introduction

Electrical Vehicles (EVs) needs four quadrant speed control operation for operating vehicles in all directions. The SRM drive is the one of the choice for driving EVs due to its high torque, high speed operation and rugged construction [1,2,3]. Although SRM drive has many advantages, it has certain limitations such as high torque ripples, acoustic noise level and vibrations. The drive design procedure and its speed toque characteristics are reported in the literature [4,5,6]. The equation of the motor gives the information about the non-linearity of the torque production. This nature of the machine can be the root cause of the acoustic noise and vibrations, if the converter switching angle is not accurate. The above said limitations were highly not acceptable in EVs and also sensor system measurement is not advisable in EVs due to high cost, size, weight and environmental factors. A new control system is developed to overcome the above said problems which has become challenging research problem for many researchers nowadays.

Normally PI based speed control system scheme is used to give the reference input for switching pulse generator. A different senosrless control methods are developed based on adaptive commutation angle and its performance are studied in past literature works [7,8,9,10]. A few method has been developed based on artificial intelligent methods such as fuzzy logic, neural networks, neuro-fuzzy [11,12,13]. Hudson et al.[14] have proposed a neural network based sensorless control system based on phase current and flux values, that requires minimum calculations to implement in DSP controller.

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 [15,16,17,18,19]. 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 transfer function based new vibration and noise reduction method using response surface methodology.

In [23] comprehensive experimental analysis has been done in order to compare the vibration and noise reduction methods. In his research work a new reduction method is implemented which includes RFPWM with robust harmonic spectrum shaping, advanced turn-on and turn-off, randomising turn-off angle and etc. The above all works deals about the system having sensor control operation. In sensorless control operation the SRM drives behaves in different manner than sensor control operation. only limited 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 is required for sensorless SRM drive operating in steady state mode in the HVAC applications. Based on the above requirements this paper explains about the advanced instrument used for vibration measurement and its analysis for sensorless variable speed SRM drive under steady state using DSP. NN based sensorless control was already tested 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, is turn -off angle randomisation has been implemented and its performance was compared with constant turn-off angle excitation.

2. Switched reluctance motor drive

A SRM drive mainly consists of motor and converter unit. The motor have stator winding called as phase winding and rotor is made of Steel iron. The motor can be classified based on the number of stator and rotor poles. However 4 phase motor having (8/6) combination of poles. The stator widings are energized sequentially by converter circuit. In literature many circuits are proposed, among that symmetrical model is popular one. Figure 1. shows the circuit diagram of the 4 phase SRM drive.

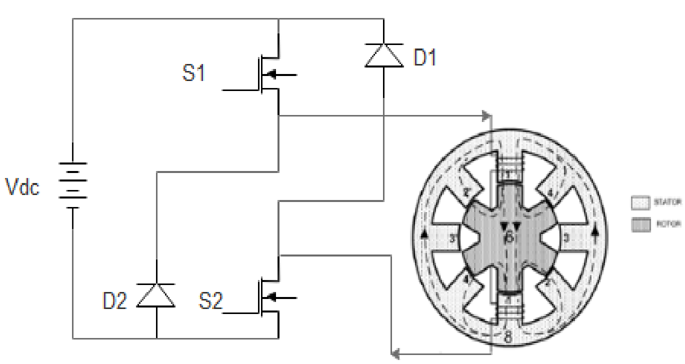


Figure 1. Circuit diagram of 4 Phase SRM drive

A modelling of Switched reluctance motor can be described as follows:
The per phase voltage equation of the motor can be written as

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

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

The per phase stator flux linkage can be expressed as (mutual phase to phase inductance is neglected)

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

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

The Total electromagnetic torque produced in the motor can be represented as

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

The mechanical load dynamics equation of system is expressed as

$$T_e = J\omega_m + B\omega_m + T_L \qquad (4)$$

Where J the moment of inertia is, B is the viscous frictional coefficient, ω_m is the rotor speed and T_L is the load torque.

A research finding has been reported in the literature work (Cai et al.,2001) that large torque ripples and notch between adjacent phase are presented in the torque waveform due to its non-ideal per phase, current wave form is generated due to improper switching commutation angle. In this work the variable commutation angle has been generated to minimize the torque ripple present in the torque values and reduce the speed oscillations in the speed response.

A New control system has been proposed based on randomized commutation angle. The commutation angle such as turn ON and turn Off angle are varied with respect to torque ripples presented in the torque waveform.A typical control system layout of the SRM drive is shown Figure2.

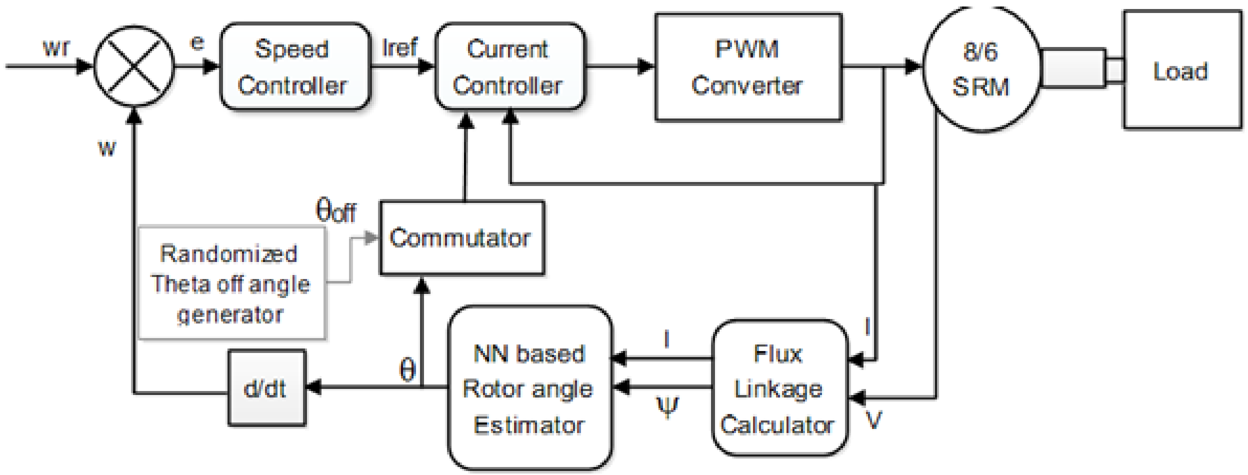


Figure 2. Proposed control system for SRM drive

A NN based rotor positon estimation algorithm has been used as a sensorless control method. NN model can predict the current rotor position based on the instantaneous flux linkage calculator and it has been tested in the previous research work[25]. The control algorithm has two loop operation namely inner loop called as current control loop and outer loop called as speed control loop both are working under different calculating time interval. A speed controller generates the reference per phase current value to the current controller and the current controller generates the reference modulation index value to the PWM generator. The motor is operating under different operating condition of EVs.

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, interaction between the currents in the stator windings produce vibration, bearing faults and other mechanical faults will lead to vibrations. Due to normal control algorithm torque ripplesare generated, is the main source for noise, under magnetic effect the noise will produce, The vibration and noise can be reduced in SR motor by proper design of motor and development of appropriate control algorithm. In this work randomized Turn off angle method is used to reduce the vibrations in SRM.

4. Randomized Turn off angle method

The randomized turn-on and turn-off angles based commutation can minimize the torque ripples, vibration, acoustic noise and speed oscillations of the SRM drive under various operating conditions, that has been reported in(Boukhobza,2001). The principle of variable commutation angles generation is shown in figure3. Though the constant Turn off and on angle are the important variables relating to the reliable operation of the drive, only the randomized values are considered to improve the performance of the drive.

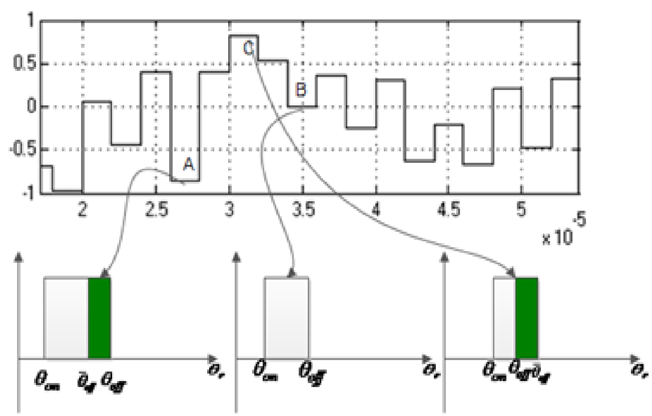


Figure 3. Principle of random variable turn-off angle generation

In this work Turn-off angle is randomly varied around the average value based on the below equation under constant Turn On angle condition

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

Where θ_{off} is the initial turn off angle, $\bar{\theta}_{off}$ is the new urn-off angle , $\Delta\theta$ is the limited band of turn-off angle variation and $y(t)$ is the random numbers generated between [-1 to +1] and it is distributed uniformly over the operating range. A variable randomized turn off angle can reduce the equivalent overlap angle of the rotor pole, So that the torque ripples and total torque can be considerably reduced per phase .

5. Experimental test bench

An Experimental test bench consists of 1 HP, 4 phase, 8/6 switched reluctance motor supplied by converter unit. An eddy current loading has been coupled with motor. Power converter unit has been built with split phase converter circuit, hall effect voltage and current sensors, over current and temperature limiter protection circuit. Encoder based position sensor are used to start the motor at initial condition and calibrate the NN based position senor values. The proposed control method has been implemented by using TMS320F2812 DSP controller and it having 16-bit fixed point CPU unit with speed of 80 ns and ADC, 16 ch. high frequency PWM ports. A PC with configuration of 3GB RAM, 2GHz speed intel processor have been used to develop the software program through TMS code composer studio. The photograph of the test bench is shown in figure4. and table 1 gives the entire specifications of the SR motor.

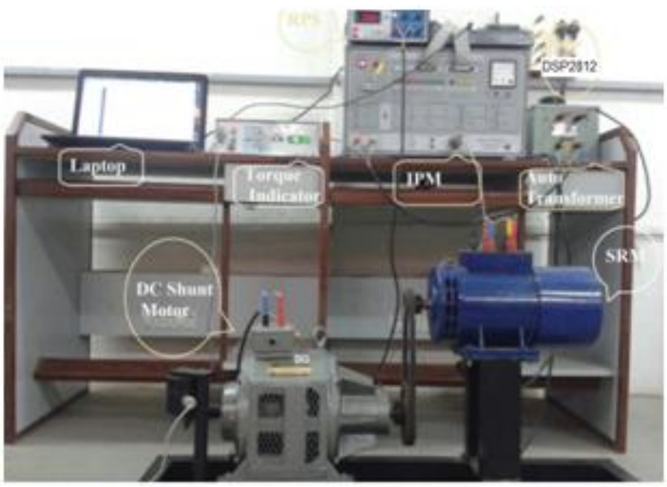


Figure 4. photograph of Experimental test bench

Table 1. Specifications of SRM

Number of Phase	4
Per phase stator pole	8
Per phase rotor pole	6
Rated per phase voltage	230V
Rated per phase current	10A
Rated speed	4000 rpm
Rated Power	0.75 kw
Moment of inertia(J)	0.005 kg-m^3
Friction coefficient(B)	0.005 Nm/(rad/s)
Per phase stator resistance (R_k)	0.050ohm

5.1 Implementation of randomised turn-off angle method

The coding for implementation of the proposed control system has been written in CCS using embedded C platform. It has been written to generate the instantaneous variable commutation angle for switching pulse design with sampling the phase current and voltage values. Figure 5. shows the flowchart for control system implementation and its process flow sequence.

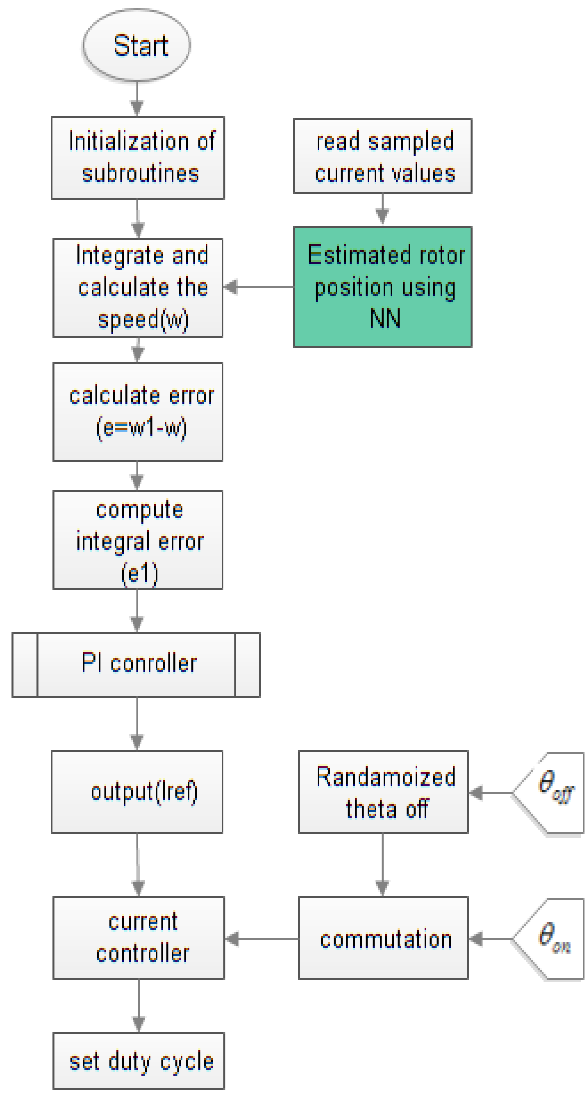


Figure 5. Implementation process of Randamoised Turn-off angle with PI controller for SRM

There are two discrete control loops functioning in the coding. First one is discrete current loop functioning at47.5µs clock speed and regulates the per phase current according to the reference per phase current given by the speed controller. The second one is discrete speed loop functioning at 22.5 µs clock speed and 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}) and Turn off angle (Θ_{off}) is 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.

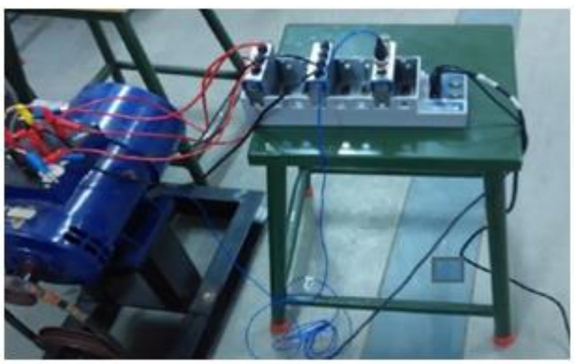
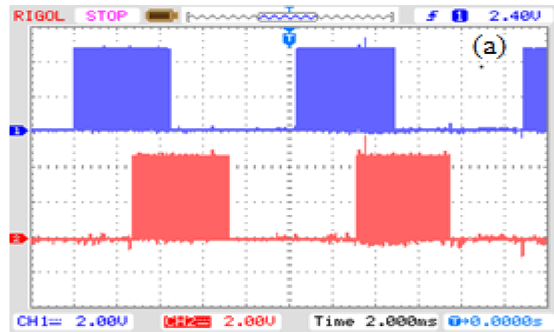


Figure 6. Photograph of advanced vibrations measurement setup

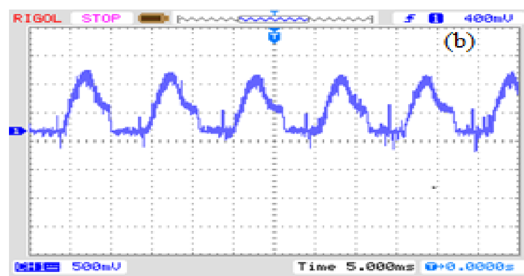
6. Experimental results and discussion

6.1 Speed and torque waveform

An experimental test has been carried out with constant commutation angles and variable commutation angles in order to check the vibration and noise level at different operating conditions of SR motor. The following experimental tests were carried out. First 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 Figure7. The pulse and current profile of constant and randomised turn off angle methods are measured using NI DAQ, which is shown Figure 8. 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

Figure 7. The switching pulse and phase current wave form at no load

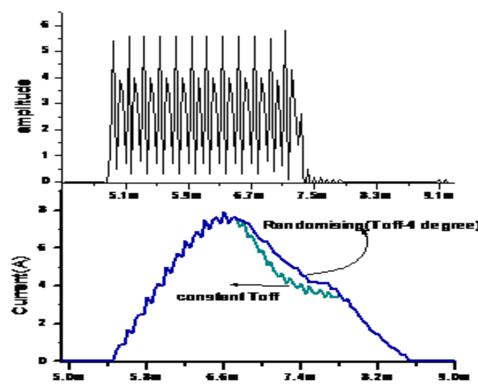


Figure 8. The switching pulse and phase current wave form at 75% of load

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 Figure9. 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 are 15 rpm in constant Toff angle method and 5 rpm in randomized Toff method.

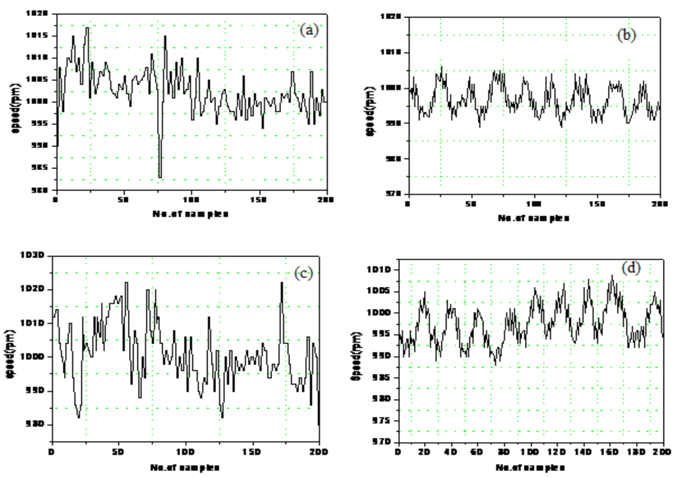


Figure 9. Steady-state measured speed at no load and 75% load (a)(c) constant Toff (b)(d) randomized Toff

Figure 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 causes more torque ripples are presented as shown in Figure10(a) the maximum 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 causes less torque ripples are presented as shown in Figure 10(b). the maximum 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 cause more torque ripples are presented as shown in Figure10(c) the maximum 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 causes less torque ripples are presented as shown in Figure10(d). the maximum torque ripple magnitude is 1.5 Nm and the number of the peak(notch between adjacent phase) occurrence is 13 for 800 samples.

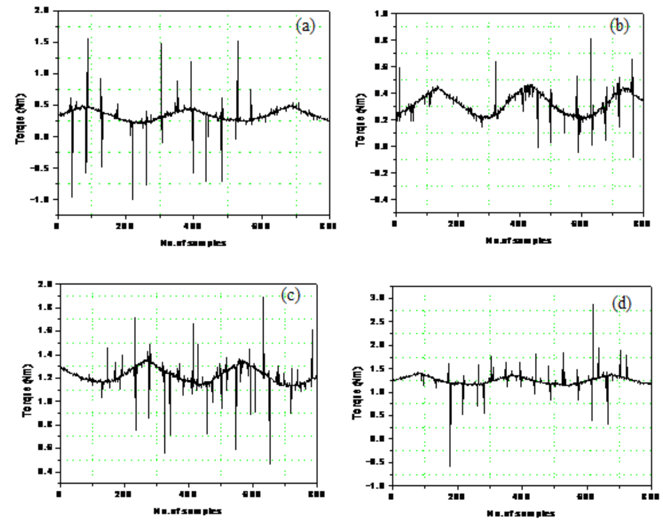


Figure 10. Steady-state measured torque at no load and 75% load (a)(c) constant Toff (b)(d) randomized Toff

7. Vibration results and analysis

The measured raw vibrations signal of SRM under different speed at constant load and different load at constant speed are shown in Figure11. and Figure 12. respectively.

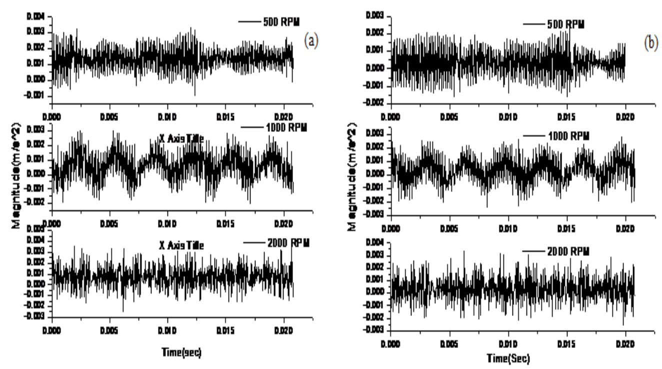


Figure 11. Measured vibrations under different speed conditions at constant load motor

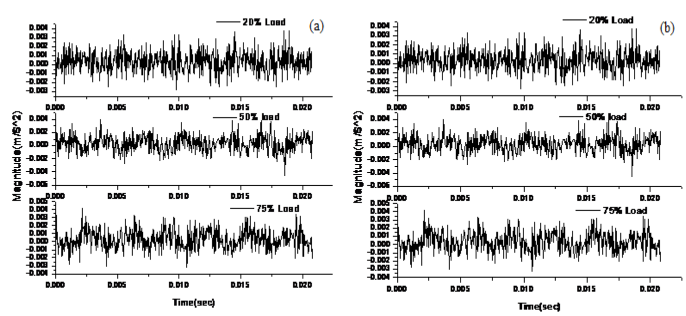


Figure 12. Measured vibrations under different load conditions at 1000 rpm

The Time domain statistics analysis such as standard deviation, peak, skewness and kurtosis are calculated for the measured vibrations signals and reported in the figure 13. and Figure14.

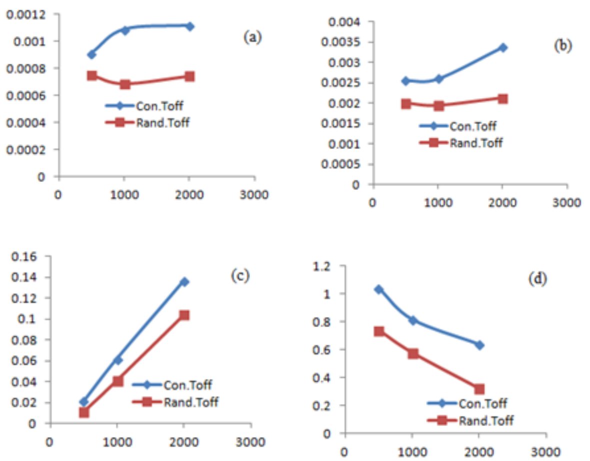


Figure 13 Time domain statistical value of vibrations signals under variable speed conditions(a) standard deviations (b)peak (c) skewness (d) kurtosis

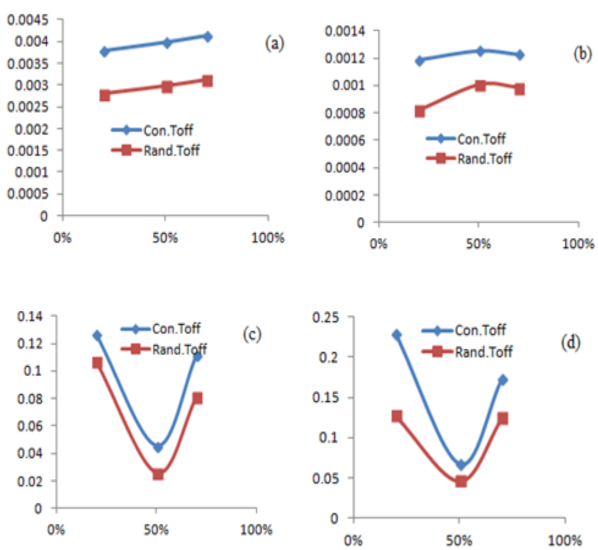


Figure 14 Time domain statistical value of vibrations signals under variable load conditions (a) standard deviations (b)peak (c) skewness (d) kurtosis

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.

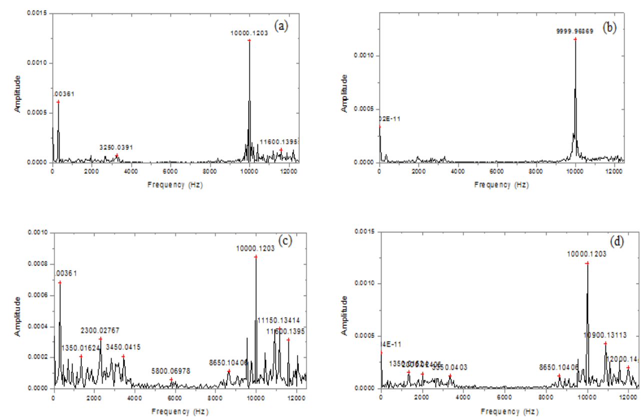


Figure 15 Frequency spectrum of vibration signals at no load and 75% load (a)(c) constant Toff angle (b)(d) randomized Toff angle

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 generator for speed control of SRM drive used in EVs and advance instruments based vibrations measurement system also presented. The vibrations signal and its higher order time domain statistical index and FFT frequency spectrum are reported under different speed and load conditions. Experimental test is carried out in 8/6 SRM drive system. The experimental results proved that the proposed speed variable commutation angle based controller maintains the motor speed at set speed with very minimum speed oscillations, torque ripples and vibrations. The randomized turn off angle method reducethe radial force during turn off so it will reduce the vibration effectively. Artificial intelligent method based vibration analysis and minimization are on-going research to extent this paper work further.

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