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Noise and Vibration Reduction in Permanent Magnet Synchronous Motors –A Review

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ABSTRACT

A detailed study of the mechanics of vibration and acoustic noise in Permanent Magnet Synchronous Motors (PMSM) due to electromagnetic origins is presented**.** This paper reviews the various noise and vibrations reduction strategies from classical to state of art techniques. The recent research in development of wavelet controller, starting from brief review and the analytical analysis of acoustic noise and vibrations in Permanent magnet synchronous motor is presented. Application of wavelet transforms in the area of denoising and filtering is also explored.

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1. INTRODUCTION

In recent years Permanent Magnet Synchronous Motor (PMSM) drives are gradually replacing induction motors drives in many application fields. This is becoming a trend due to some key features of PM motors, including compactness, efficiency, and robustness, reliability, and shape adaptation to the working environment.Permanent magnet synchronous motors are well accepted in high performance applications requiring quieter operation. Generally, they exhibit low noise compared to their counterparts intended for similar applications. The high performances applications by nature require smooth operation hence demand low torque ripple. Though loosely connected, the vibration characteristics of a motor very often are related to its torque ripple contents. The term “quiet operation” should not misled for lower cogging torque and torque ripple only rather it should meant for less vibration and noise. These are two separate entities. Lower torque ripple in PM motor ensures smooth running of the motor and does not guarantee less vibration or noise. The electromagnetic radial forces when acts on the stator cause vibration in a PM motor. Acoustic noise emitted by an electric machine can be viewed as a phenomenon by which the electromagnetic forces and the stator frame interact. Noise and vibration are two phenomena linked in an electrical machine. Normally, the radiated noise is the effect of a vibrating surface; therefore, the sources of noise and vibration are the same. There are three main sources of acoustic noise in electrical machine, namely, aerodynamic, mechanical, and electromagnetic. The electromagnetic source is the dominating source in low to medium power rated machines. Cogging torque, torque ripple and magnetic radial forces are the main electromagnetic sources of noise and vibration. According to several researchers, the reduction of cogging torque and torque ripple can significantly reduce the vibration and acoustic noise [1-6]. In order to reduce mechanical vibrations, various studies are analyzed [4-6]. In practical applications, control gains are limited under resonant frequency band to suppress the source signal within mechanical one. Although this approach can be easily implemented, the dynamic performance of control system is decreased by the control gain. In some applications, the stiffer mechanical joint using additional devices are used due to get higher of the resonant frequency of the system.

The wavelet transform and other space frequency or space scale approaches are now considered standard tools by researchers in signal processing, and many applications have been proposed that point out the interest of these techniques. In audio and, more precisely, automatic speech analysis, wavelets are currently in operational software. However, even if promising practical results in machine vision for industrial applications have recently been obtained, the wavelet transform in operational industrial products is still rarely used, and, too often, space-scale processing tools fail to be included in industrialist imaging projects. The reason may be the, sometimes abstruse, mathematics involved in wavelet textbooks or the false faith in the omnipotence of this new approach, leading to disappointing experiences. Be that as it may, it seems more necessary than ever to propose opportunities for exchanges between practitioners and researchers about wavelets. In this respect, this paper aims at reviewing the recent published work dealing with acoustic noise in electrical machines using the wavelet and, more generally speaking, multiresolution analysis.

In section II, Origin of noise in PMSM, in section III, Wavelet transform basics is expressed, in section IV, Overview of Noise and Vibration Reduction Strategies. In section V Merits and Demerits of wavelets are expressed.

2. ORIGIN OF NOISE IN PMSM

The acoustic noise in permanent magnet synchronous machines is low compared to the noise generated by switched reluctance and induction machines; yet, quieter performance is desired in automotive and robotics applications. Acoustic noise emitted by an electric machine can be viewed as a phenomenon by which the electromagnetic forces and the stator frame interact. Noise and vibration are two phenomena linked in an electrical machine. Normally, the radiated noise is the effect of a vibrating surface; therefore, the sources of noise and vibration are the same. Figure 1 shows the various sources of acoustic noise in Electric motors. Noise and vibration in PM machines can be classified into three categories based on its source: aerodynamic, mechanical, and electromagnetic. The acoustic noise generated by the mechanical and aerodynamic sources is mainly connected to the mechanical structure of the electric motor. The magnetic force acting on the cores of the stator and rotor may produce troublesome noise and vibration, especially when the frequencies of the exciting forces are equal or near to the natural frequencies of the machine concerned. In most of the practical cases, the predominant acoustic noise is produced by the radial force.

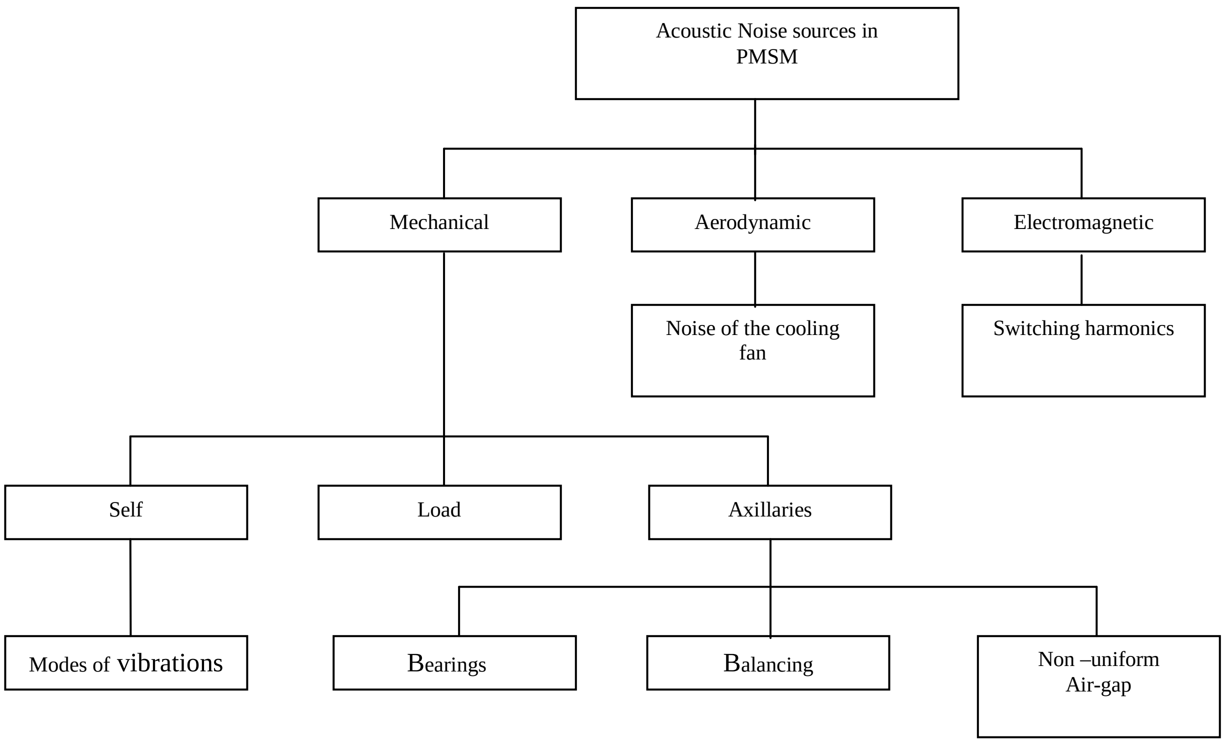


Figure 1. Acoustic noise sources in electrical motors

For electrical machines with a rated power lower than 15 kW and rotational speed lower than 1500 rpm, the main source of acoustic noise is from the electromagnetic origin [8].

2.1. Electromagnetic Sources

Electromagnetic forces contributing to the vibration and acoustic noise of an electric machine can be classified as,

[i] **Forces acting on the surface of the stator teeth**: These forces are normal to the surface of the iron and are responsible for the majority of the radial and tangential vibration in an electric machine. A complete analysis of radial and tangential electromagnetic forces in PMSM is proposed in .

[ii] **Forces acting on current carrying stator windings:** These forces can initiate vibration in the coils, which may lead to failure of insulation and short-circuit. This in turn can cause permanent damage into the stator laminations (due to large magnitude of the short circuit current). These forces are referred to as Laplace forces.

[iii] **Magnetostrictive forces are another cause of vibration:** These forces are caused in lieu of subjecting a ferromagnetic material to an external magnetic field. Heavily saturated stators subject to fast changing magnetic fields can result in significantly large magnetostrictive forces.

The electromagnetic source is the dominating source in low to medium power rated machines. Cogging torque, torque ripple and magnetic radial forces are the main electromagnetic sources of noise and vibration. According to several researchers, the reduction of cogging torque and torque ripple can significantly reduce the vibration and acoustic noise [1-7]. Each of these research works proposed a rather complex method for reduction of noise and vibration of the system.

3. WAVELET TRANSFORMS

Basically, as a Short-time Fourier Transforms (STFT), the Wavelet Transform (WT) is a means of obtaining a representation of both the time and frequency content of a signal. But, in WT, the window function width is dependent on the central frequency [7, 9, and 10]. Therefore, for a given analysis function, the best trade-off between time and frequency resolution is automatically obtained and kept. A wavelet is a kernel function used in an integral transform. The wavelet transform of a continuous signal $x(t)$is given by

$$W_{a,b}(t)=\int_{-\infty}^{\infty} x(t)\,\psi_{a,b}^{*}(t)\,dt. \tag{1}$$

With the wavelet function defined by dilating and translating a “mother” functions as

$$\psi_{a,b}(t)=\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

where $\psi(t)$ is the “mother” wavelet, a is the dilation factor (a real and positive number), and b is the translation parameter(a real number) If the wavelet function is well chosen, it is said to be admissible, and computing the original function from its wavelet transform is possible. If the wavelet is reasonably localized, the admissibility condition is simply

$$\int_{-\infty}^{+\infty} \psi(t)dt = 0 \tag{3}$$

For practical reasons, the dilation and translation parameters are often discretized; leading to the so-called discrete wavelet transform (DWT) after discretization, the wavelet function is defined as

$$\psi_{j,k}(t) = 2^{-j/2}\,\psi(2^{-j}t-k) \tag{4}$$

There are different mother wavelets like: Haar, Mexican Hat, Morlet, Meyer, Daubechies, Raspl and others more.

[i] **Mexican hat:** useful for detection in computer vision. It is the second derivative of a Gaussian function.
[ii] **Haar:** The first wavelet, introduced in 1909. It's simple definition is helpful for computing wavelet transforms, but because it is not continuous, it is not as useful as other wavelets for analyzing continuous signals.
[iii] **Daubechies-2p:** Wavelets with p vanishing moments, to represent poly-nomials of degree at most p − 1. A Daubechies-2 wavelet is equivalent to the Haar wavelet. As p increases, signals can be represented using fewer coefficients, due to fewer scales being required.

The wavelet transform is a very efficient tool for scale-time (or scale-space in imaging applications) signal analysis, characterization, and processing. Its scale discrimination properties are widely used for practical applications in algorithms of denoising (selective coefficients thresholding), scale filtering (different from classical frequency filtering) fractal analysis, or scalogram visualization. Its capability to organize and concentrate information is also one of the main reasons for the WT's success in image compression.

3.1. Selection of Wavelets

The Continuous Wavelet Transform (CWT) leads to a continuous representation in the scale space domain. It allows a fine exploration of the signal behavior through a scale range but is a highly redundant representation. The reconstruction process (inverse transform) is generally a very time-consuming task. Therefore, the CWT is used mainly for 1D signal processing and when no synthesis is required. For images, and if the original signal is to be reconstructed after analysis, one prefers the Discrete wavelet transform and generally its simple dyadic version presented in Eq.(1) The DWT can be performed in a non- redundant scheme following the decimated algorithms proposed by Mallat or Sweldens or, if translation invariance is necessary, in a redundant algorithm (nondecimated or "a-trous" algorithm) The wavelet set can constitute an orthogonal basis or, relaxing some constraints, a bi-orthogonal basis or even a simple frame. More generally, the choice of the wavelet kernel is driven by some properties to be verified. The most important and commonly considered properties are the regularity, the number of vanishing moments, and the compactness. The regularity or number _integer or not_ of continuous derivatives indicates how smooth the wavelet is. Its localization in the frequency domain is directly connected to this regularity: the larger the regularity, the faster the decrease in Fourier space [9, 10]. The number of vanishing moments is linked to the number of oscillations of the wavelet (localization in space). More importantly, if a wavelet has *k* vanishing moments, it kills all the polynomials of degree equal to or lower than *k* in a signal. The size of the wavelet's support is also an important issue: the longer this support, the higher the computational power required for the WT. The maximum number of vanishing moments is proportional to the size of the support. If a wavelet is *k* times differentiable, it has at least *k* vanishing moments. Therefore, a trade-off between computational power and analysis accuracy and between time resolution and frequency resolution must be achieved in each given problem.

4. OVERVIEW OF NOISE AND VIBRATION REDUCTION STRATEGIES

In the following sections Research work of several researchers in field of reduction of acoustic noise and vibration in electrical machines is summarized as:

Fahimi *et al.* propose a new method to reduce the vibrations of electrical machines by means of a control on the torque ripple without requiring any knowledge of the back electromotive force [12]; however, it needs a Hall-effect sensor and a torque ripple sensor. Moreover, Vas [13] proposes several control schemes or reducing the torque ripple and decreasing the vibrations of the local forces on the teeth, but it needs difficult tuning of the controller parameters for a suitable reduction over a wide range of mechanical loads and rotating speeds.

In paper [14], the author proposes an original approach for the control of the switched reluctance machine to reduce the stator vibrations by the optimal displacement of piezoelectric actuator. However, all these works are active methods for noise and vibration control. As for these passive techniques, two strategies are usually followed to reduce vibration and noise: the geometric redesign of the machine to change its resonance frequencies [15–17] or the use of materials with some particular damping characteristics. Recent Research has shown that the use of wavelet analysis in signal de-noising is in many ways similar to the open-loop control techniques used for synchronous rotor vibration control. Therefore in following section some of the applications of wavelets in noise and vibration reduction in PMSM are discussed briefly.

Yoshinari Asano *et al*. have said vibration of concentrated winding motors tends to be higher than distributed winding motors. This phenomenon is caused by the projection of radial stress. In this paper, it is said that for the concentrated winding motors the radial stress becomes partly large which makes deformation of the stator core. Therefore, air gap length where radial force is large has been enlarged. Figure 2 shows that the radial stress in the air gap becomes smooth by enlarging the air gap partly and consequently the vibration of the motors can also be reduced [18].

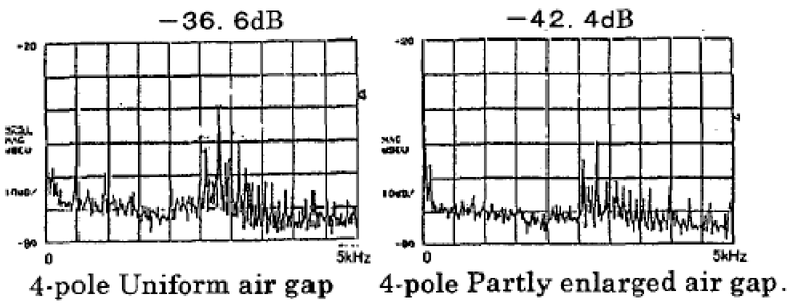


Figure 2. Motor vibration in radial direction of permanent magnet synchronous motor

Patrick S. Keogh, *et al.* explored research undertaken to utilize wavelet analysis in the closed loop control of rotor/active magnetic bearing systems. The closed loop controller is formulated in the wavelet coefficient domain using real-time evaluation of the wavelet transform, which involves a signal processing delay. The controller was designed to minimize the wavelet coefficients of measured rotor vibration signals. Hence, this implies that the rotor vibration will be attenuated by the control action. The figure 3 shows the schematic block diagram of the fault identification process [19]. It was found that the controller was able to minimize wavelet coefficients with pseudo-frequencies matching the synchronous frequency of the rotor.

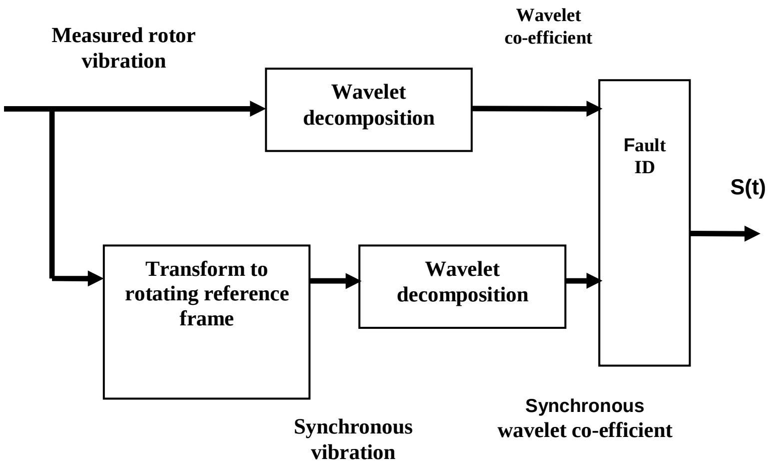


Figure 3. Block diagram showing faults identification procedure

Researcher in [20] addresses the problem of Signal identification in electric drives applications. In this paper two applications of wavelets on electric drives are presented. Initially wavelets are used to denoise experimentally taken current measurements from an inverter fed drive which works under a constant voltage/Hertz control strategy. Various wavelets and levels of decomposition have been used and compared with conventional filtering methods. Through that detailed comparison it is shown that, for on-line applications, conventional filtering methods based on FIR filters should be preferred. There are two main problems that are associated with this wavelet usage: increased complexity and the inherent delay present due to the use of multiple sample times.

Based on this observation the author proposes a novel pseudo-adaptive denoising method that is based on wavelets which adjust the level of decomposition depending on the synchronous speed of the induction machine. The new adaptive method reduces the integral of the squared error more than 200 times. This novel application of wavelet denoising makes it more attractive for on-line applications but still it may not be preferred to conventional filtering methods in such simple applications. It was found that experimentally and numerically that wavelets are superior to conventional methods in such applications. Wavelets denoise and do not smooth the signal without taking into account the frequency area of the spurious signals. The denoising scheme based on the WT did not distort the signal and the noise component after the process was small as shown in figure. 4.

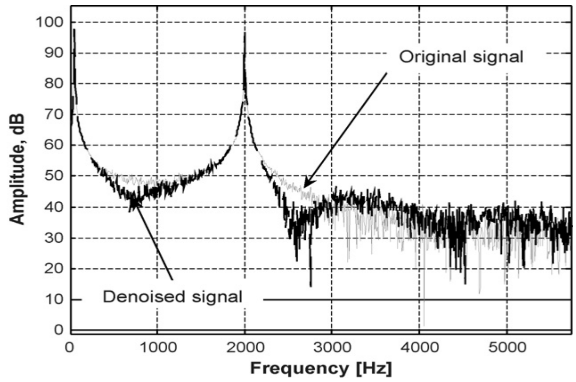


Figure 4. Frequency Spectrum of original and De-noised signal

Sang-Ho Lee *et al.*(2008) made a study on the acoustic noise reduction according to the change of the pole angle in interior permanent magnet (IPM) motor with concentrated winding. It consisted the analysis of mechanical and magnetic noise sources, optimal design using response surface methodology which is to reduce the harmonic component of magnetic forces at the stator tooth, and the comparison with cogging torque, torque fluctuation, the harmonic components which affect the stator tooth, and acoustic noise between prototype and optimal model under the rated operating condition. Results shows total noise of optimal model is better than prototype, respectively as shown in figure 5. The noise of prototype is generated from the resonant frequency band of stator and PWM frequency band. The noise of optimal model only is generated from the resonant frequency band of stator but its overall noise value is lower than that of prototype. The reason is that inductance of prototype is lower than optimal model due to the increase in magnetic saturation by the reduction in pole angle.

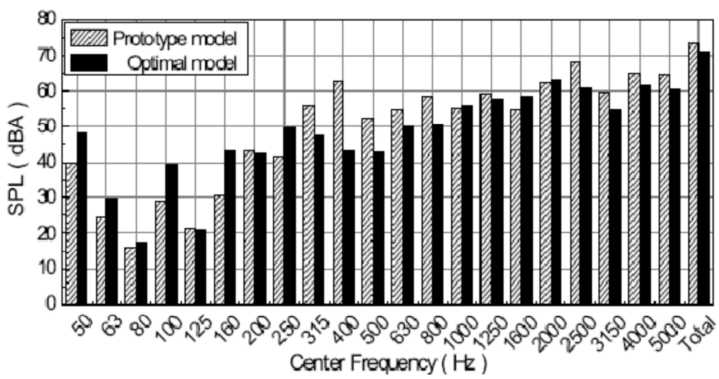


Figure 5. Comparison with Noise Spectra between Prototype and Optimal model

Minh-Khai Nguyen *et al.* (2009) [22] uses the fact that if harmonic spectra are decreased, then acoustic noise also decreased. In the paper, we deal with a simple and effective method using random modulated strategy and random PWM technique for a switched reluctance motor. This technique plays an essential role in a significant reduction acoustic noise by combining the varying turn-on, turn-off angle and random PWM scheme. While target of random turn-on, turn-off angle technique is to decrease amplitude of the fundamental harmonics, random PWM technique is to provide harmonic spectra intensity flatter than that obtained by conventional method. This combination will help avoiding the triggering mechanical resonances. Thus, the harmonic spectra of output voltage in SRM are reduced significantly. As shown in figure 6a for conventional method, the amplitude of the all components is more dominant than that as shown in figure 6b for the proposed method. Sub-harmonics in area (a) of figure 6b are smaller than these of figure 6a. The results confirm that the new proposed method provide better harmonic spectra performance than conventional strategies in spreading the harmonic power over a wide frequency range.

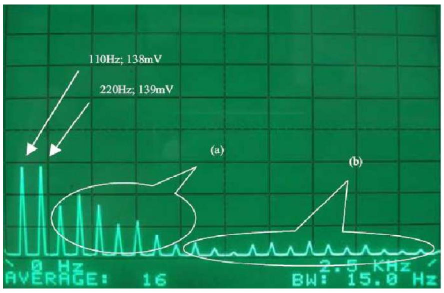


Figure 6a. Conventional Method with chopping mode

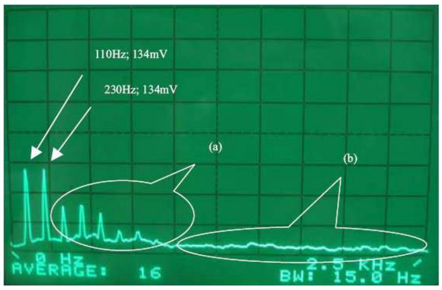
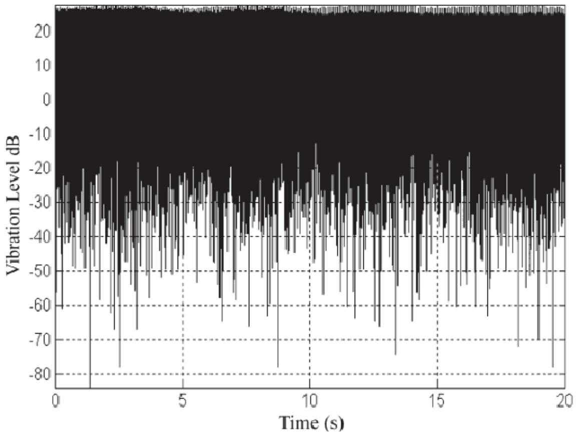


Figure 6b. Proposed Method with chopping mode

N. N. Hashemi *et al.* (2009) [23] focused on acoustic noise which has an electromagnetic origin and a novel strategy for reducing acoustic noise using an actively controlled approach is presented. Author suggests in this paper that avoiding the excitation of motor resonance frequencies can be a key factor in a noise control strategy. As a new approach to this problem, the authors have developed a strategy whereby acoustic feedback is used to modify the inverter control strategy “on the fly”. This is based on the notion that the typical inverter voltage-frequency characteristic (the “constant *v/f* approach”) can be altered in order to achieve a given speed/torque operating condition using a range of different drive frequencies. Author stated that by means of the active control strategy, it is possible to optimise the behaviour of the inverter in order to achieve the full range of load operating conditions, while avoiding the excitation of resonant conditions which can lead to high noise levels.

Ahmad Arshan Khan *et.al.* [24] has said the estimation of rotor position at low speed is heavily affected by the signal processing used for extracting the high frequency current signal in carrier signal injection based sensorless control algorithm. The permanent magnet motor is excited by injecting high frequency voltage signal onto the d-axis of the rotating reference frame. This high frequency voltage signal excites the high frequency impedance of the motor, which contain the position information. In this paper, author used physical phase variable model of Permanent Magnet motor. It inherits the accuracy of finite element model and has a fast computational speed. The design of the signal processing unit is one of most critical issues which need close attention in low speed sensorless algorithms. The type of band pass filter is going to effect the position estimation performance. In this paper wavelet based filtering approach are compared with commonly used 1st order Butterworth’s band pass filter and inference is drawn that sensorless control algorithm using wavelet based filtering gives better estimation performance even at low injection voltage. The wavelet based filtering approach outperforms Butterworth filter for low values of injection voltage. The improvement in filtering can be attributed to the fact that the wavelets are better in extracting a particular frequency band signal than 1st order Butterworth’s band pass filter as shown in figure 7a and 7b.



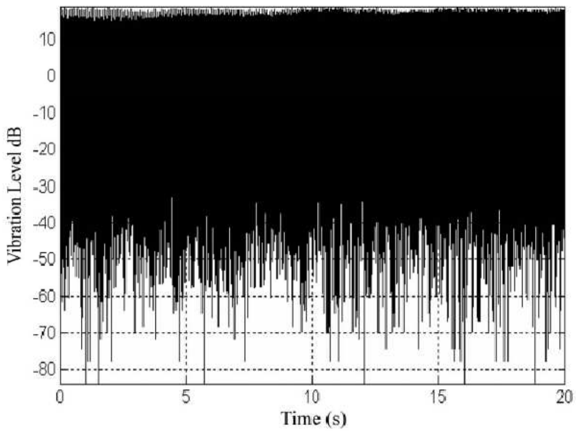


Figure 7a. Vibration level in the Starting structure Figure 7b. Vibration level in the Modified Structure

Dimitri Torregrossa *et al.* Proposed a 3-D finite-element modal analysis to reduce the acoustical power radiated by brushless permanent-magnet synchronous machines and avoid any resonance phenomena. The method is able to analyze the impact of some design parameters on all the resonance frequencies for reducing the total sound power and gives some guidelines to their choice**.** This paper proposes a passive methodology to achieve a global reduction of the acoustic emitted sound power, so that it will be independent of the rotating speeds and amplitude currents. A passive reduction does not need any direct action on electromagnetic forces or harmonic current by the converter controller. The aim of the passive reduction is to avoid the resonance structural phenomena in the PMSM.The main interest of passive reduction techniques for vibration and sound emission is their independence on the power converter supply and passive methodology is use to avoid resonance phenomena.

Rakib Islam *et al*. analyze the noise and vibration in permanent- magnet synchronous motors (PMSMs). Electromagnetic forces have been identified as the main cause of noise and vibration in these machines, rather than the torque ripple and cogging torque [25]. An analytical model has been developed to determine radial deformation using radial pressure as the input. The analytical model is validated by the structural FEA and by accelerometer tests predicting radial displacement. The radial displacement thus calculated is used to estimate noise and vibration in different PMSM configurations. This research showed that the root cause of noise and vibration is the radial forces not the torque ripples.

B. Sutthiphornsombat *et al. (2010)* has presented a numerically efficient method to effectively mitigate the effects of acoustics noise and vibration in PMSM for optimization [27]. Field reconstruction method (FRM) is presented and used to mitigate the acoustic noise and vibration in PMSM drives by computing the electromagnetic torque and radial forces of PMSM. The FRM utilizes the three phase current profile and rotor position to calculate radial and tangential components of the force density and the flux density as shown in Figure 8. Furthermore, FRM can predict torque ripple originated from geometry of the machine.

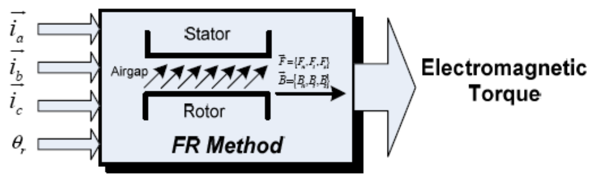


Figure 8. Block diagram of field reconstruction method

Nicolas Bracikowski *et al.* have modeled a permanent magnet synchronous machine by lumped models using finite element analysis. Several fields of physics, such as electromagnetic, thermics, mechanics and acoustics are necessary for designing electrical machines. Although certain well-known finite element analysis (*FEA*) tools are capable of computing these different motor characteristics, coupling them can be painstaking and often prohibitive in terms of computational time, particularly in optimization processes. In order to solve this problem, we use lumped models that are perhaps slightly less precise than FEA but faster. Author has linked these lumped models to the mechanical and vibratory model in order to determine in first the torque and harmonics but also vibrations and electromagnetic noise.

Yongxiang Xu *et al.* proposed two periodic frequency modulation patterns, including triangular and sawtooth periodic frequency modulation, to reduce the acoustic noise [29]. In the PMSM (Permanent-Magnet Synchronism Motor) driven by fixed switching frequency inverter, the acoustic noise spectrum has highly concentrated harmonic energy near switching frequency and its multiples. In this paper, triangular and sawtooth periodic switching frequency modulation patterns are proposed to transfer these discrete power spectrum to more wider frequency ranges, so as to limit the acoustic noise at low cost. Author has said periodic frequency modulation is effective in spreading the spectrum to wider frequency ranges and reducing the acoustic noise as shown in figure 9a and 9b.

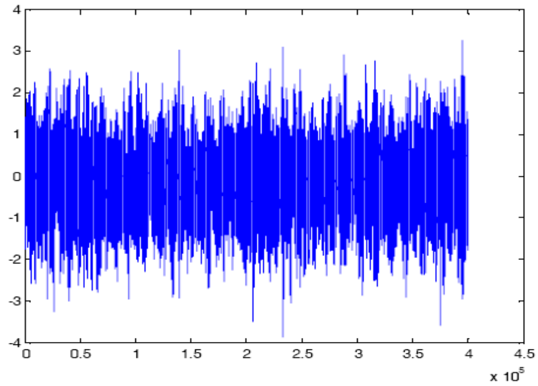


Figure 9a. Motor Vibration before Optimization

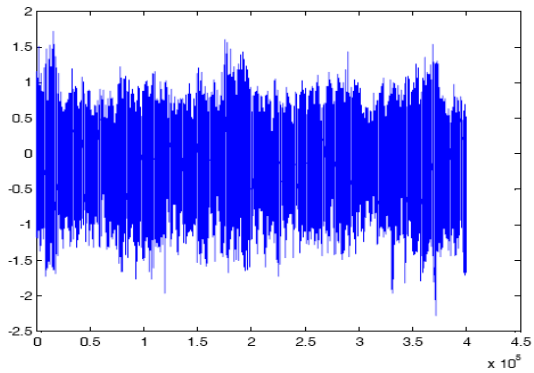


Figure 9b. Motor Vibration after vibration Optimization

Arash Nejadpak *et al* [30] has presented an online gain scheduling of the Wavelet-based controller coefficients for the purpose of reducing noise and vibration resulting from a sensorless control of PM machines at low speeds. The Wavelet-based controller decomposes the whole frequency spectrum into several sub-bands. Each sub-band has a unique effect on the position and speed estimation error in the transient and steady state conditions. The high frequency bands mostly affect the noise and vibration of the system.Genetic Algorithm (GA) is used to optimize the effective parameters in sensorless control of the PMSM, in order to improve the steady state response of position, speed estimation and reduce vibration of the motor. GA is a population based global search procedure which is inspired by natural selection and genetics law. An overall improvement in position estimation error was achieved. After performing online optimization, the error is reduced by 5% as shown in figure 9a and 9b.

Research work of several researchers in field of reduction of acoustic noise and vibration in electrical machines is summarized as there are two main techniques to reduce vibration and noise of electrical machines: active techniques by developing a special control of the motors and passive techniques by modifying the motor design (geometry and materials). Many kinds of wavelet transforms and wavelet basis are involved. The main contributions of the wavelets are their capability to provide time-scale analysis (scalograms, transient detection and characterization, feature extraction)or multiscale analysis (characterization of fractal behavior, texture analysis)and to organize information in a signal (compression) and the reversibility of the WT (for filtering and denoising).

5. MERITS AND LIMITATION

Wavelets possess two properties that make them especially valuable for data analysis: they reveal local properties of data and they allow multi scale analysis. Conventional methods have difficulty distinguishing between noise and the modulated rotor speed, while wavelets are successful in reducing the mean squared error. The power of wavelets was revealed mainly because they represent a uniform and easy way of extracting time varying frequency components. This information can be used for effective denoising or compressing which is accomplished in a totally different way to conventional filtering or compressing methods. A significant advantage of the wavelet controller is the reduction in the computational burden and consequently the execution time.

There are two main problems that are associated with this wavelet usage: increased complexity and the inherent delay present due to the use of multiple sample times. Another property of the wavelets which has been used in electric drives is their ability to detect anomalies in current measurements that are present due to various faults that appear in the machine. The complexity of the WT can cause problems when used in real time applications, and in such a case would offer no advantage.

From above review it is sighted that WC performs slightly better than a PID, however it performs much better noise rejection Noise is an important factor that effects control system performance. It is a well established fact that noise restricts the bandwidth of the control system and reduces system stability. Therefore using a wavelet controller offers distinct advantage of improving system bandwidth and stability.

6. CONCLUSION

The Electromagnetic forces are the main cause of noise and vibration PMSM, rather than the torque ripple and cogging torque and it is also found that the root cause of noise and vibration is the radial forces not the torque ripples. The acoustic noise in electric machines has close correlation between the resonant frequencies of stator and the harmonics of normal force. The research travels through exploitation of multi scale analysis and they reveal local property of data in wavelet transform features. Most promising areas of applications are denoising and those where classical control solutions cannot provide satisfactory performance, typically when the model of the plant is not available or highly non-linear, or when the system is subject to significant parameter variation. It is found that wavelet performs better noise rejection and contributes towards improving system bandwidth and stability. As per recent research noise and vibration reduction using wavelets are better than conventional methods. Application of wavelets to electric drives is continuing to flourish in the near future this opens the area for research.

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