B. TECH. PROJECT REPORT

On

Noise Control of Electric Vehicles

BY

Bhukya. Siva Naik(170003012)

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

May 2022

Noise Control of Electrical Vehicles

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
Bhukya. Siva Naik(170003012)

Guided by:
Prof. Anand Parey

INDIAN INSTITUTE OF TECHNOLOGY INDORE
<May 23, 2022>

CANDIDATE’S DECLARATION

I hereby declare that the project entitled **“Noise Control of Electric Vehicles ”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Prof. Anand Parey,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

B Siva Nook
27-05-2022

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

27/05/2022

Signature of BTP Guide(s) with dates and their designation

Preface

This report on “Noise Control of Electric Vehicles" is prepared under the guidance of Prof. Anand Parey.

(Through this report I have tried to give a detailed design of an Electric motor’s rotor for the Electric vehicles and try to cover every aspect of the new design, if the design is technically and economically sound and feasible.

I have tried to the best of my abilities and knowledge to explain the content in a lucid manner. We have also added 3-D models and figures Designed in Catia V5R21 and Ansys Maxwell to make it more illustrative.)

Bhukya. Siva Naik
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

Acknowledgements

I wish to thank Prof. Anand Parey for his kind support and valuable guidance.

It is their help and support, due to which I became able to complete the design and technical report.

Without their support this report would not have been possible.

Bhukya. Siva Naik(170003012)
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

Abstract

Due to their very low to zero carbon emissions, low noise, great efficiency, and flexibility in grid operation and integration, Electric Vehicles (EVs) are a viable technology for establishing a sustainable transportation sector in the future. However, there are considerable obstacles to the widespread adoption of electric vehicles, including battery technology constraints, high purchasing costs, and a lack of recharging infrastructure, NVH problem for electric vehicle.

The high frequency electromagnetic noise emitted from electric power train system could significantly affect the driving comfort and has become an important NVH problem of electric vehicles. One of the primary issues with electric vehicles is noise reduction, as noise range of electric motors is distinct from that of traditional ICEs, and human insight is considerably more vulnerable to it.

In this work, taking IPMSM for electric vehicles Electromagnetic forces, for example, were investigated using an ANSYS work bench and a multiple physical field finite - element framework. The main cause of EM noise is the electromagnetism of the motor's stator teeth. We can optimize the slot structure of a rotor to To optimize a magnetic field of rotor, enhance EM vibrations of stators tooth and reduce the EM vibrations of motor. So, in this experiment, the electromagnetic noise of the stator is lowered by refining the design and changing the shape of the IPMSM rotor. We offer two distinct rotor structures for this purpose. By comparing and analysing the EM forces, acoustic field, and magnetic field of different structures, as well as comparing their outcomes before and after optimization, the most suited structure may be discovered.

Table of Contents

List of Figures

List of Tables

1.INTRODUCTION

1.1 Electric Vehicles

A vehicle with single or several electric motors for traction is known as an electric vehicle (EV). A collector system can be used to power that uses electricity from outside the vehicle, alternatively it might be self-driven by a batteries that solar panels energize them, or a generator. These EV's do not only road and railway power trains , but also for land and watercraft, electric aeroplanes, etc are all examples of electric vehicles.

1.1.1 Types of Electric Vehicles

There are three main types of Electric Vehicles

1) Hybrid Electric Vehicles

2) Plug-in Electric Vehicles

3) Battery Electric vehicles

Hybrid Electric Vehicles : In (HEVs), an ICE works in conjunction with electric motors that draw energy from batteries. High fuel economy and low tailpipe emissions are combined with the power and range of conventional vehicles in HEVs.

Plug-in Electric Vehicles: A PHEV is a vehicle with a rechargeable battery pack that can be recharged both internally and externally, via a charging cable plugged in to external electricity source, and internally, using its ICE -powered generator.

Battery Electric vehicles: A battery electric vehicle (BEV), also known as a pure electric vehicle. A BEV is a type of electric vehicle that gets its traction purely from stored chemical energy in recharge battery packs. Internal combustion engines (ICEs) are replaced with electric motors and motor controllers in BEVs.

Electric vehicles are far more efficient than conventional automobiles and emit far fewer direct emissions. They still, nevertheless, depends on electricity for their operation, which is often produced by a mix of fossil fuel and non-fossil fuel plants. As a result, by changing the source of electricity, Overall, EVs can be designed to be less polluting. In some regions, residents can request that their electricity be generated using renewable energy. They can also work in tandem with regenerative braking systems, It is capable of converting motion energy to stored power This can be used to lessen the wear on the braking system. (and thus brake pad dust), as well as the total energy required for a journey. Regenerative braking is particularly useful for stop-and-go city driving.

1.2 Electric Motor:

A rotary electric motor provides motion in the systems described above. An electric motor is a mechanical machine that converts electrical energy. Most electric motors generate force in the form of torque on the motor's shaft by interacting between the magnetic field of the motor and electric current in a wire winding. An electric generator is physically equivalent to an electric motor, but it converts mechanical energy into electrical energy using a reversed flow of power.

Electric motors are divided into three categories: AC motors, DC motors, and special purpose motors.

Most commonly employed electric motors in electric vehicles are AC motors and which again divided into two sub categories:

1) Induction motor
2) Synchronous motor

1.2.1 Induction motor:

A common AC electric motor is an induction motor (sometimes known as asynchronous motor). The electric current required to produce torque in an induction motor is acquired through electromagnetic induction from stator winding's revolving magnetic field. An induction motor's rotor can be either a squirrel cage rotor or a wound type rotor.

There are different kinds of induction motors available in market.

1.2.2 Synchronous Electric motor:

The shaft rotation of a synchronous electric motor is synchronised with the frequency of the supplied 3 phase current at steady state, and The amount of AC cycles in the time frame is indeed an integral number. Multiphase AC electromagnets here on stator produce a magnetic field which rotates in time with line current fluctuations in synchronous motors. The rotor, which is made up of permanent magnets or electromagnets, rotates at the same rate as the stator field, resulting in the second synchronised revolving any AC motor's magnet field If a synchronous motor's rotor and stator are both equipped by independently excited multi stage AC electromagnets, it is referred to as doubly fed.

In this paper we will discuss synchronous motors

Types of synchronous motors:

1) RELUCTANCE MOTORS

2) PERMANENT MAGNET SYNCHRONOUS MOTORS

3) NON EXCITED MOTORS

In this paper we discuss PERMANENT MAGNET SYNCHRONOUS MOTOR

Because of its great efficiency of power density, the PMSM design is frequently chosen, despite its downsides like as cost and complexity.

1.3 **Working principle of PMSM:**

When set side by side to conventional motors, PMSM's operation is relatively simple, quick, and efficient. The spinning magnetic field of the stator and the constant magnetic field of the rotor are required for PMSM to function. The rotor is made up of permanent magnets that provide a continuous magnetic flux and operate and lock at synchronous speeds.

The phasor groups are created by linking the stator's windings together. These phasor groups are connected to produce various connections, such as a star, Delta, double, and single phase. The windings must be wound close together to reduce harmonic voltages.

When a 3-phase AC supply is applied to the stator, it produces a revolving magnetic field, while the permanent magnet of the rotor induces a constant magnetic field. This rotor rotates at the same time as the synchronous speed. With no load, the whole operation of the PMSM is dependent on the air gap here between stator and rotor.

The motor's windage losses will be reduced if the air gap is big. The permanent magnet's field poles are extremely important. Permanent magnet synchronous motors do not start themselves. As a result, electronic control of the stator's variable frequency is required.

1.3.1 **Types of PMSM:**

Permanent magnet synchronous motors are categorised into two types based about how magnets are adjusted to rotor and the rotor design:

Interior permanent magnet synchronous motor (IPMSM)

surface permanent magnet synchronous motor (SPMSM)

SPMSM connects all magnet pieces to the surface, whereas IPMSM puts magnets inside the rotor

SPMSM connects all magnet pieces to the surface, whereas IPMSM puts magnets inside the rotor..

1.4 **Noise in Electric Vehicles:**

Even though Internal Combustion Engine is absent in pure electric vehicles there several sources of noise and vibration in electric vehicles creating Noise, Vibration, Harshness(NVH)problem in electric vehicles creating problem to driver and passenger. Vehicle NVH characteristics and ride comfort have become more essential aspects in meeting customer desire for a better driving experience.

To accomplish these functions without the need for a vehicle to drive air conditioners and heating, windows, and other mechanical components, a variety of electric supplementary devices will be required. Each of these devices introduces vibration and acoustic issues that, while modest separately, might add up to be considerable when combined.

However, if the ICEV's noise masking feature is not used, structure-borne noise out from suspensions in an EV will become more noticeable, however the interior noise will diminish whenever the EV is driven at a reasonable speed. To reduce interior noise in an EV and increase sound quality, it is vital to identify the sources of suspension structure-borne noise. However, because the suspension system has multiple parts and noise sources, identifying and reducing suspension structure-borne disturbance in an EV is a difficult undertaking.

In automotive powertrains, gear noise inside the transmission system is a significant source of noise. A great number of articles have addressed transmission system gear noise. Theodossiades presented an analytical method for predicting the airborne sound levels of gear teeth as well as the dynamic characteristics of gear pairs under a variety of operating scenarios. The findings revealed that harmonics in the drive shaft speed cause increased gear-noise emission.

The majority of an electric vehicle's life is spent travelling between 30 and 45 miles per hour. Wind noise is still modest at this speed, and motor noise is generally hidden by road and tyre noise. As a result, road and tyre noise will be the most prominent noise heard by EV drivers and passengers.

In electric motor, the most common and complex sort of noise in most electric machinery is electromagnetic noise, which is the subject of this paper. The vibrations produced by electromagnetic forces inside the motor, from which the radial force on the stator tooth surface is the major component, are referred to as electromagnetic noise. However, there are a number of noise-generating mechanisms that are caused by the presence or change of electromagnetic fields.

2.Literature review

Permanent - magnet motors for cars are known for their light weight, simple build, great efficiency and stable operation. They've been seen in a lot of new energy cars from big manufacturers. (NVH) accomplishment metrics of the new energy cars are becoming more and more relevant in the automobile industry as humans expectations for sound as the cost of driving continues to grow.

Electric motors, unlike traditional autos, have superseded ICE as the primary source of vehicle power. As a result, several researchers have begun to focus on improving the NVH performance of automotive motors.

Control power noise and structure noise are two types of motor noise. Electromagnetic noise understructure noise is the principal source of vibration noise in permanent magnet synchronous motors for electric vehicles (EV's). Many academics have studied the electromagnetic noise produced by motors.

In ref[1] structural design By refining the magnetic isolation bridge for the rotor construction, the goal of modifying the electromagnetic excitation force of the stator teeth was realised, and the motor's vibration and noise were reduced.

In ref[2] presented a teeth tip arc of a stator offset structure that moves the initial teeth tip arc in the towards radius of the stator's diameter for a predetermined to increase the magnetic field of the stator spatial structure, force uniformity, and vibration reduction.

In ref[3] Starting with stator teeth chamfering, we examined the flux in air gap densities equation of partial when the stator teeth chamfering in a permanent magnet motor, and determined the the amplitudes of harmonics at various teeth chamfering angles. At last, the Here, the teeth chamfering process has an impact on the motor's EM noise and vibration is calculated and analysed using the theoratical formula and finite element model

The optimized and enhance the stator with no making change in slot area's frequency, the stator yoke width (b) and slotted angle (d) associated parameters of the stator slot were increased.[4]

In (5,6) Using Ansys and LMS simulation analytical technical tool, the deflection degree of the stator slots was evaluated and an acceptable deflection angle was established.

The impact of the Harmonics of saturation flux density at low-speed and high-load operation conditions, as well as the Density harmonics of magnetic flux produced by the strong magnetic deformation due to a On the motor's electromagnetic noise, a high field dampening operation is performed, was studied in the later stages of motor control. Vibrations and noise from motors can be dangerous. examined and optimised using the digital pulse width modulation (PWM) theory.[7]

In Ref[8] tested the motor's noise performance under various stator skew factors The sounds of the permanent magnet synchronous motor were evaluated after selecting the optimal stator structure to confirm the simulated analysis results. Each rotor is stepped and constructed with variable leaning degree, and the rotor is distributed evenly along the axial direction. The effect of stator slots that are offset which is capable of efficiently lower the teeth resonance of a motor waveform and enhance the Permanent - magnet motor torque ripple, is similar to this structural architecture.

In summary, permanent-magnet motors is a study on noise and electromagnetic vibration mitigation measures, The primary goal was to improve pole-to-slot alignment, optimising the stator tooth tip design, as well as Further active noise control approaches used the rotor's slanted pole, and so on. There is currently minimal research on the effect of the In permanent-magnet motors, the effect of rotor slit design on noise and electromagnetic vibration. Because of its simple structure and excellent efficiency, synchronous permanent-magnet motors of the "V" type configuration have been commonly applied in the area of electric cars. As a result, research into noise and electromagnetic vibration for such a sort of motor is crucial.[10,11,12,13,14,15]

The effect of Circuit noise by EM force was investigated. The radial electromagnetic force created in the space 0-order mode of fc+/3f1 and 2fc is discovered to cause electromagnetic noise and vibration. PWM harmonics are proven to create the EM radial forces of fc+/3f1 and 2fc. In Ref[17,18], they also employed PWM control technology and primarily developed a PWM speed control technique depending on PI. PWM control system and functional prototypes were validated based on the idea of an actual interface system through simulation, and noise and vibration exploratory method of the BLDC motor was managed to carry out Using the FPGA board to achieve the optimization effect.

Maxwell forces are EM forces acting stator tooth; they have always been perpendicular to the metal substrate which are the most important kind of EM noise, to the point where they are frequently the only ones investigated. [19,20]

The perpendicular component causes rotor teeth snapping oscillations, torque pulsing, and rippling in addition to providing the acting torque that matches the electromagnetic torque. Because it operates on the stator's internal surface core and teeth, causing housing deformation, Most of the noise in PMSMs comes from EM radial component of Maxwell stress. [21,22]

Strong magnetic forces: electric steel used for making the electric motor core, which is susceptible to strong magnetic forces when exposed to a high and quickly shifting outermost magnetic field, causing oscillation in the electric motor. [23]

A parasitic torque known as cogging torque is caused by the electromagnetic attractive force produced in between stator core and PM in rotor (CT). Despite the fact that CT is a cause of loss, many researchers overestimate its contribution to the whole noise spectrum when classifying it among the principal sources, because reduced CT does not indicate less noise and vibration output. Furthermore, the authors show that CT is not just caused by the motor's electromagnetic characteristics, but that poor assembly or manufacturing tolerances can also contribute significantly to its harmonics.[24]

3.Objective

The main aim of this work is to reduce the noise impact of Electric motor on Electric vehicles. The specific objectives of this work are

1. To look into state of the art mechanisms from the literature for the noise suppression and identify the noise control strategies that can be implemented on the electric motor(PMSM).

2. To illustrate a process for the design of a PMSM's motors rotor and then implement the modifications to reduce the noise occurring from the Electric motor.
3. To perform the vibroacoustic analysis using Ffoucs Maxwell's stress tensor equation in Ansys Maxwell's workbench and validate the contours of Acoustic sound level.

4.Structural Design

The research item in this article is an 80 kW constructed "V" style permanent - magnet drive motor. According to theoretical studies, the principal reason of electromagnetic vibration in electric motors, is an imbalance in the radial electromagnetic force, it has to be completed. The vibration and noise parameters of the motor are calculated using the finite element method, and the rotor slit design is then altered to increase the magnetic field of the motor and reduce NVH. Two distinct rotor slit designs were constructed, differentiate, and assessed, with the best rotor slit design based on the expected outcome being chosen and thoroughly investigated.

4.1 Basic Parameters and Models of v shape PMSM:

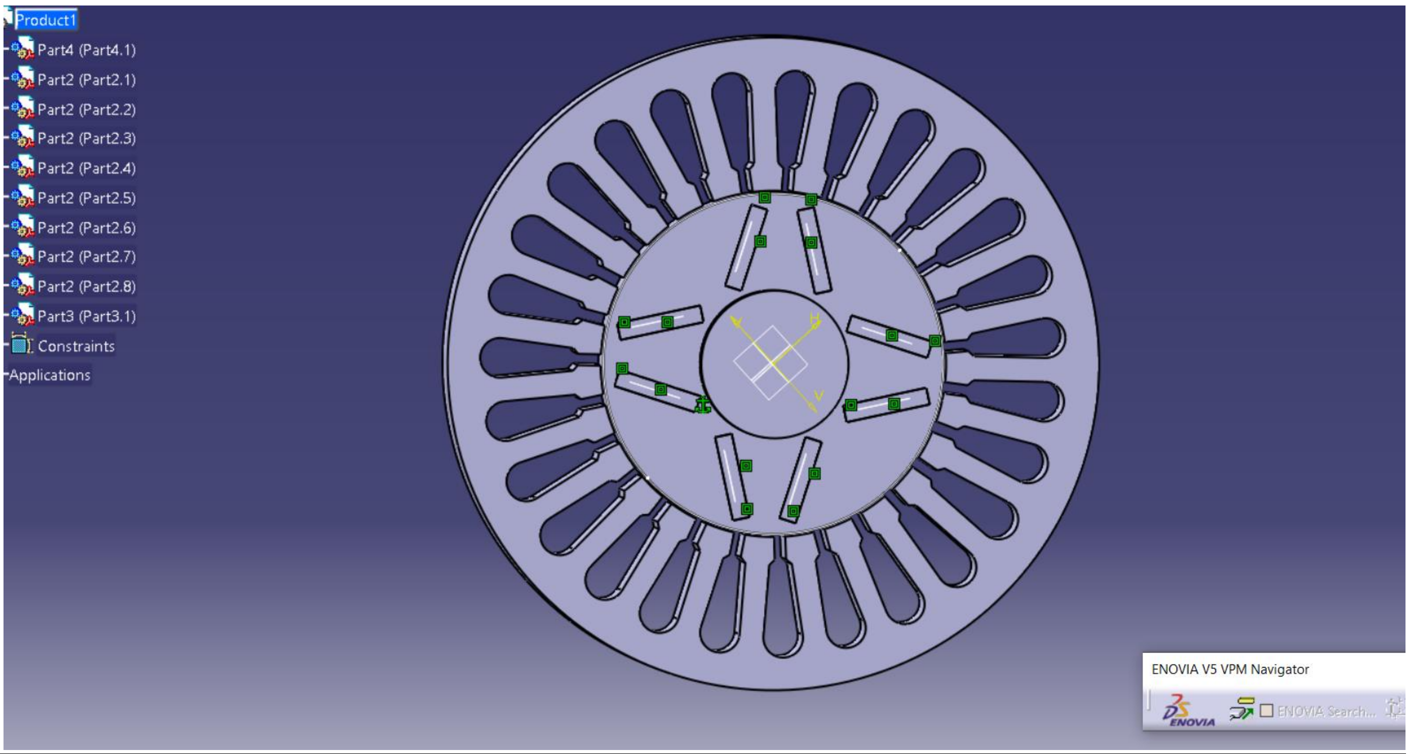
This model is an 8-pole 30-slot "V"-shaped permanent - magnet motor with a designed permanent – magnet drive motor for the automobile as a study subject. The basic parameters of a motor are shown in Table 1. A 3D modeling of motor was created in CATIA programme using the basic characteristics of the motor, and suitable simplifying was accomplished out to assist the finite element model, it was created and calculation was executed. Figure 1 depicts the 3D model.

Table 1. Parameters of PMSM.

- parameters	value
Stator outer diameter	180 mm
Rotor outer diameter	110 mm
Stator inner diameter	112mm
pole	8mm
Maximum speed	10000 rpm
Rated speed	4000 rpm
Frequency	195 Hz
Core length	160mm
Efficiency	90%
Rotor inner diameter	55 mm
Maximum power	160 Kilowatt
Air gap length	

Phase (3)	2 mm
Power	80 kilowatt
Number of slots	30

Figure:1 Basic Motor structure:



Because electromagnetic vibration noise is the main source of motor noise, and unbalanced radial electromagnetic force during motor rotation is main affect of motor EM vibration noise, If you want to learn about motor's EM noise and vibration, we must first carry out the calculations and analyses on the electromagnetic radial forces of motor.

The radial electromagnetic force concentration on the stator tooth surface can be determined using the Maxwell Stress Tensor Method (MSTM) hypothesis. The unit of measurement is N/m2.

$$f_r = \frac{1}{2\mu_0}(B_r^2 - B_t^2)$$

B_t is the tangential element of a magnetic flux in the air gap of a motor density, unit: T. B_r and B_s are the tangential and radial components of motor air gap magnetic flux density, respectively. The vacuum permeability is μ_0.

The μ_o of ferromagnetic substances is significantly larger than field lines, and those of air enter the rotor cores and stator almost at right angles to face the iron core's. As a result, the magnetic density of such tangential air gap is significantly less than the magnetic strength of radial air gap, which could possibly be overlooked. The stator core structure's radial electromagnetic force is about is given below

$$f_r = \frac{B_r^2}{2\mu_0}$$

Magnetic Flux Φ_B at the motor's air gap is mostly made up by the rotor's permanent MMF and the magnetic density generated by the stator.

$$B_r = B_{r\delta} + B_{s\delta}$$

And is given by

$$B_{r\delta} = F_R \lambda_\delta$$

$$B_{s\delta} = F_S \lambda_\delta$$

F_R-air gap magnetomotive Force

F_s-Stators magnetomotive force

$$F_r = \sum_{v_r} F_{R_m}^{v_R} \cos v_R\,(p\theta - \omega t)$$

$$F_s = \sum_{\mu} \sum_{v_S} F_{m\varphi}^{\mu,v_S} \cos(v_S p\theta - \mu\omega t + \varphi^{\mu,v_S})$$

$$\lambda_\delta = \lambda_0 + \sum_{k_z}^{\infty} \lambda_{k_z} \cos k_z\, z_0 \theta \text{ where } k_z = 1,2,3, \ldots.$$

$F_{R_M}^{v_R}$- Air gap harmonics amplitude

λ_0- avg permeance of air gap

$F_{m\varphi}^{\mu,v_s}$- Amplitude of MMF of stator current

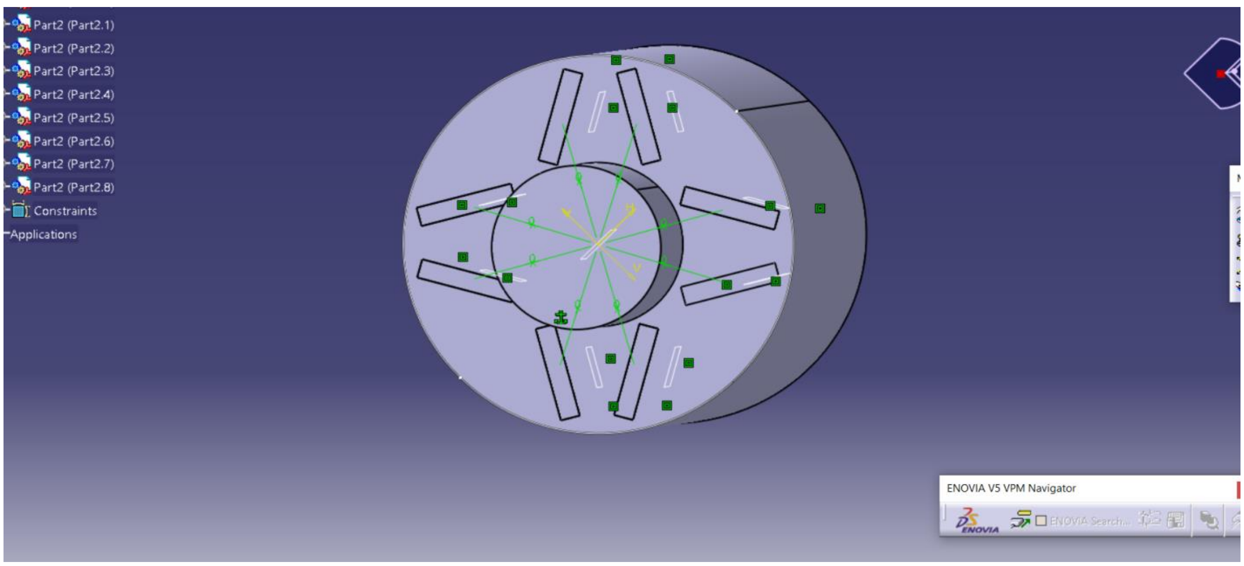
φ^{μ,v_s}-intial phase angle

The electromagnetic force wave of the low-order EM radial force is quite high, resulting in increased vibration and noise. The magnitude of the EM force wave is already modest whenever the order is increased, as well as the effect is even negligible

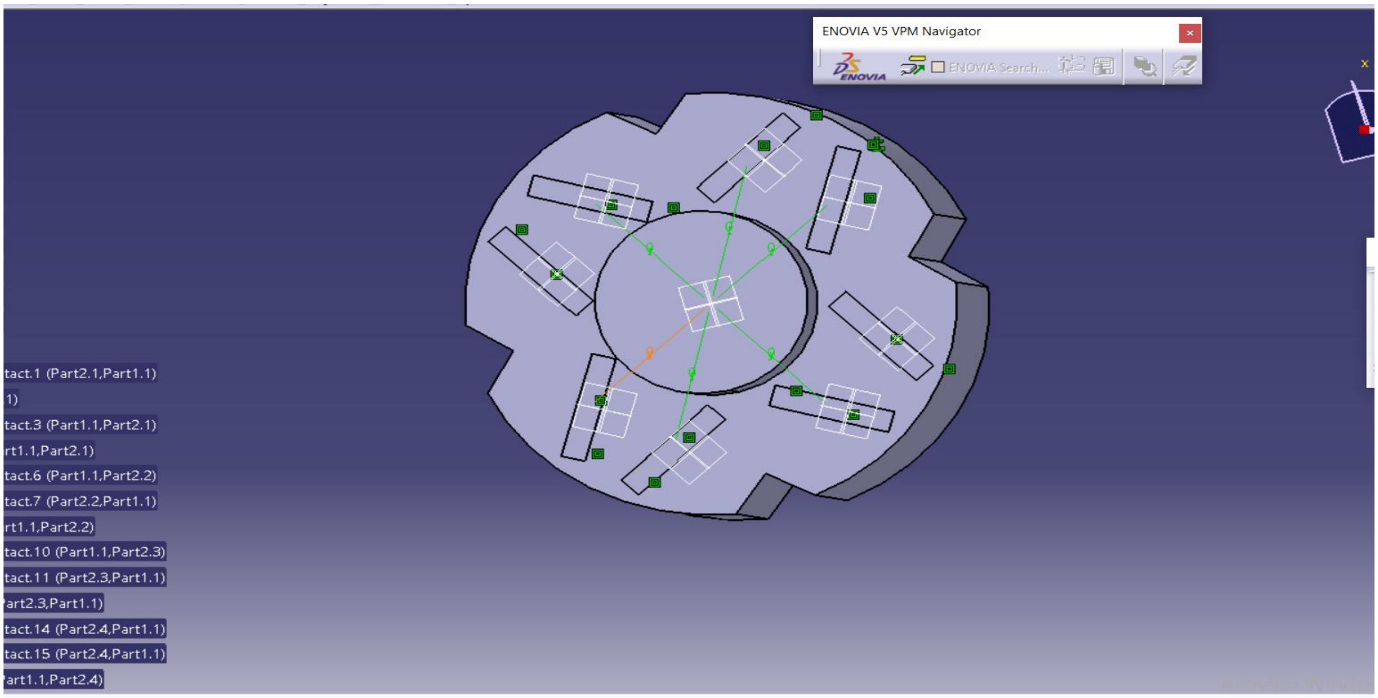
5.Structural Optimization

The motor's radial electromagnetic force f_r should be lowered in order to improve electromagnetic vibration and noise. The amount of the electromagnetic force is determined by the radial air gap flux density B_r and B_s, as shown in formula (3), and the radial flux density of motor will be influenced Whereas if magnetic circuit of the motor is altered. As a result, two types of rotor thin slot structures are proposed in this study, each of which optimises the orientation of the motor's magnetic circuit. Figure 2 depicts the structure of the motor under specific optimization technique. "V" kinds are the optimal rotor structures. The "Basic" type of rotor is the one that hasn't been optimised.

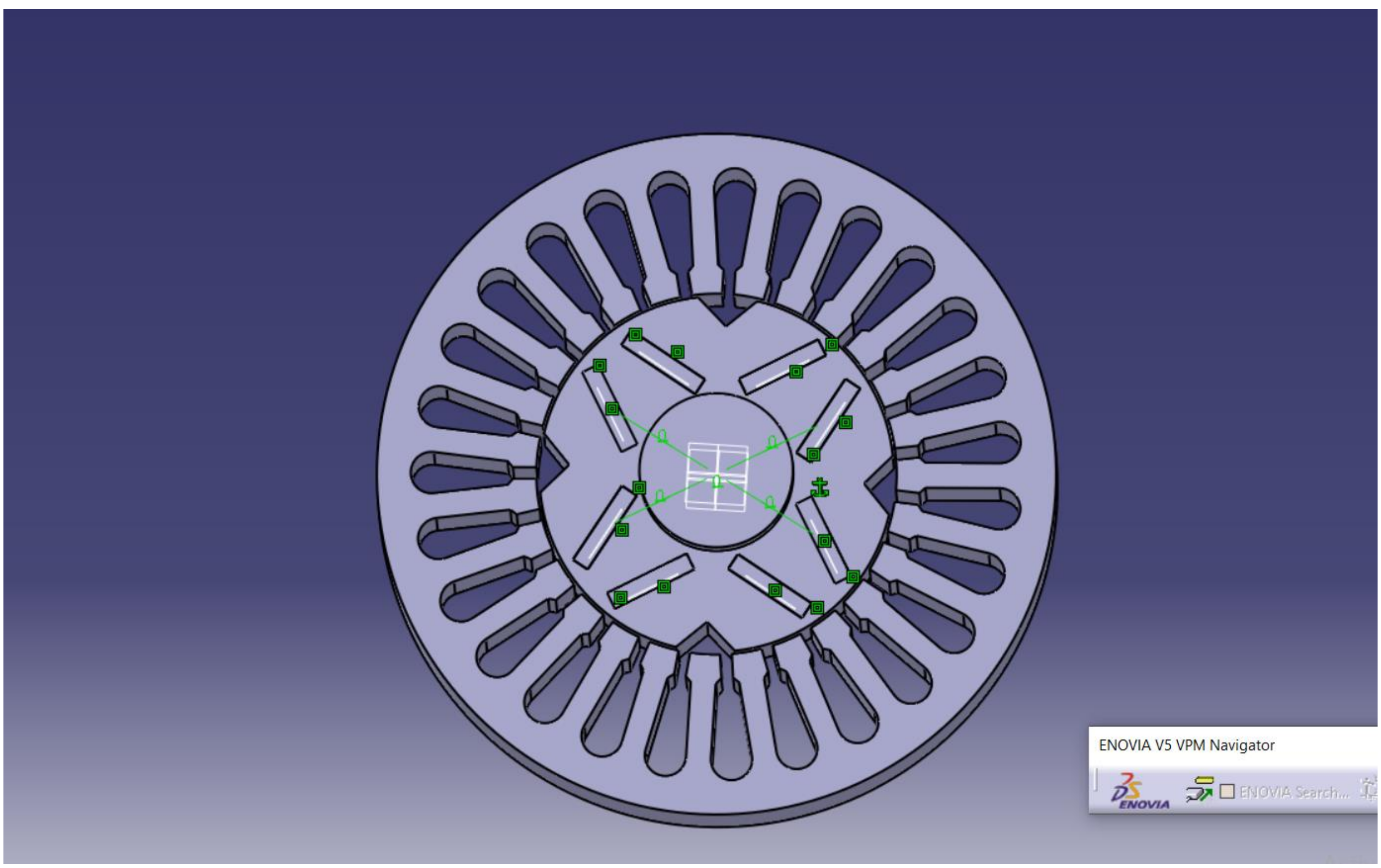
Figure:2 Two rotor structures



1. Basic model



2.Modified rotor structure



3.Modified electric motor

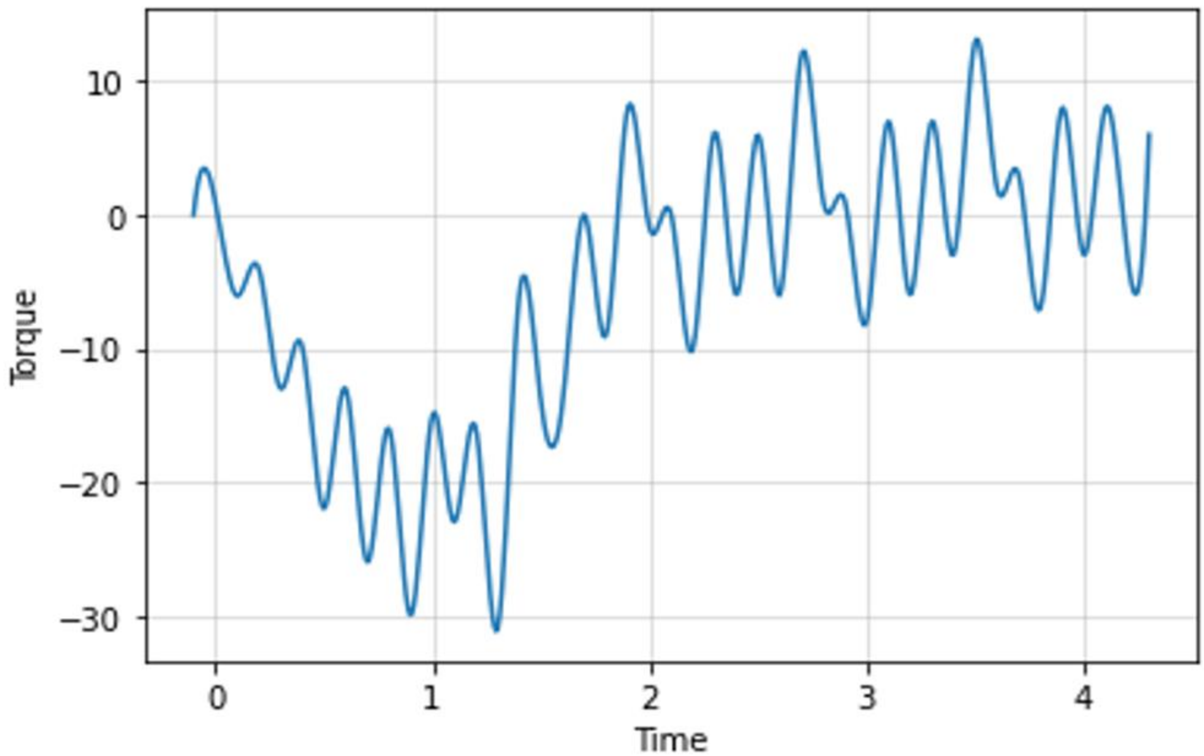
The rotor slit design is adjusted as a result of the initial shape and alters the various degrees of the magnetic circuit's orientation, improving the motor's reluctance and decreasing the corresponding magnetic gap. Simultaneously, the new rotor design reduces the rotor's mechanical sturdiness to a degree, therefore the mechanical strength is monitored. Silicon steel sheet is used for the rotor, and it has a yield strength of 390 MPa. The two optimised rotors are subjected to a stress study. The mechanical sturdiness of rotor can be guaranteed to meet the criteria if stress produced more by rotor in the twirl condition is below its yield limit.

6.Magnetic field analysis

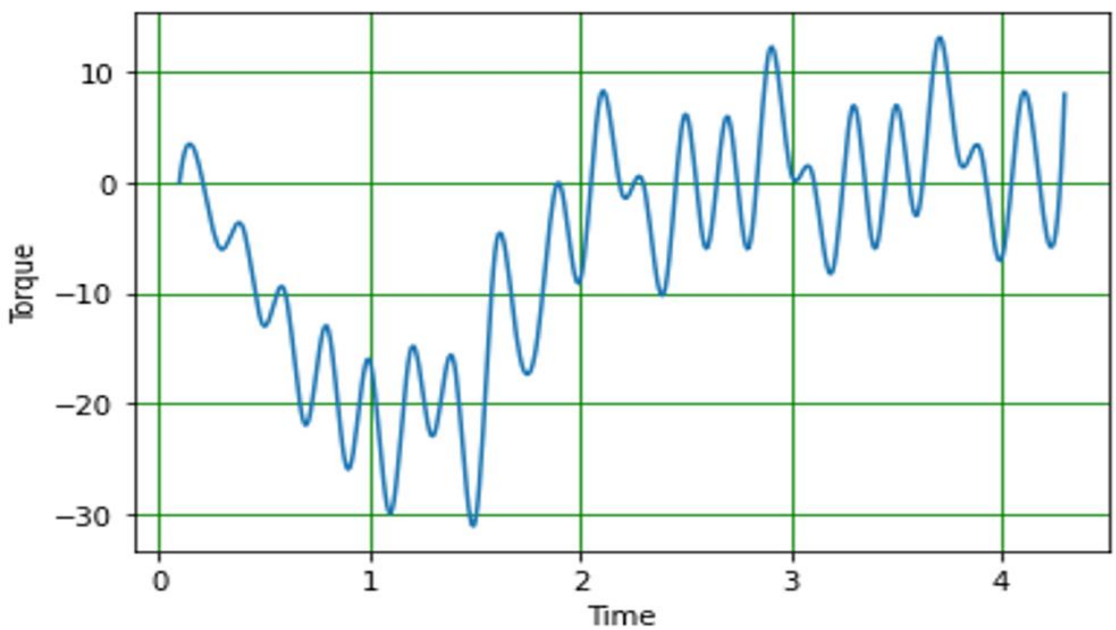
The magnetic field of the motor having the rotor slit design can be analysed using Maxwell software once the new rotor design is created in CATIA. The two different rotor slit structures can be seen from result increasing the motor's reluctance and achieving the goal of shifting motor's magnetic circuit direction to varying degrees.

The magnetic flux cloud diagram, on the other hand, can only reveal that the motor's magnetic circuit has changed, not that the new rotor design electromagnetic noise effect on the motor has changed. The torque change diagram for the motor is shown in Figure 3. The torque depicted on torque graph is tangential torque of motor, which does not produce noise or vibration under normal working conditions. Two types of optimised motors for the slit design are proposed, and torque ripple from 0 to 3ms phase is greatly decreased, that help minimize the anomalous noise produced by tangential torque ripple by the motor's during startup. Furthermore, during motor's steady functioning phase, torque fluctuation, the amplitude of the two lines are almost same. As a result, under the assumption of altering the orientation of magnetic circuit of motor, the slit structure will have no effect on the motor's output power, and it will have no effect on the motor's output performance.

Figure-3 torque change graph



1

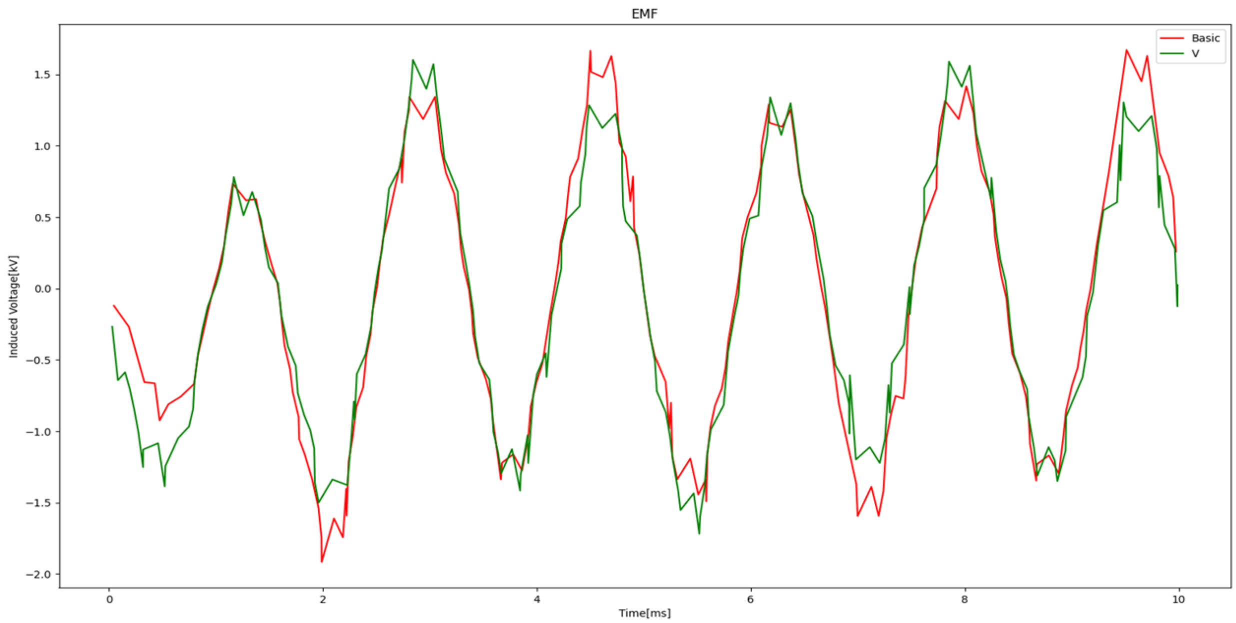


2

1)Torque graph of basic structure. 2)modified rotor structure

The maxima of two generated EM forces are similar when comparing two simulation outcomes, The v-type motor, on the other hand, appears to have the lowest generated electromotive force variation and the best effect during the startup period. This can be seen from below results

Figure-4 Waveform of induced EMF:



Here the red curve indicates induced EMF of basic structure and green line indicates the induced EMF V-type rotor

7.Electromagnetic Noise Test

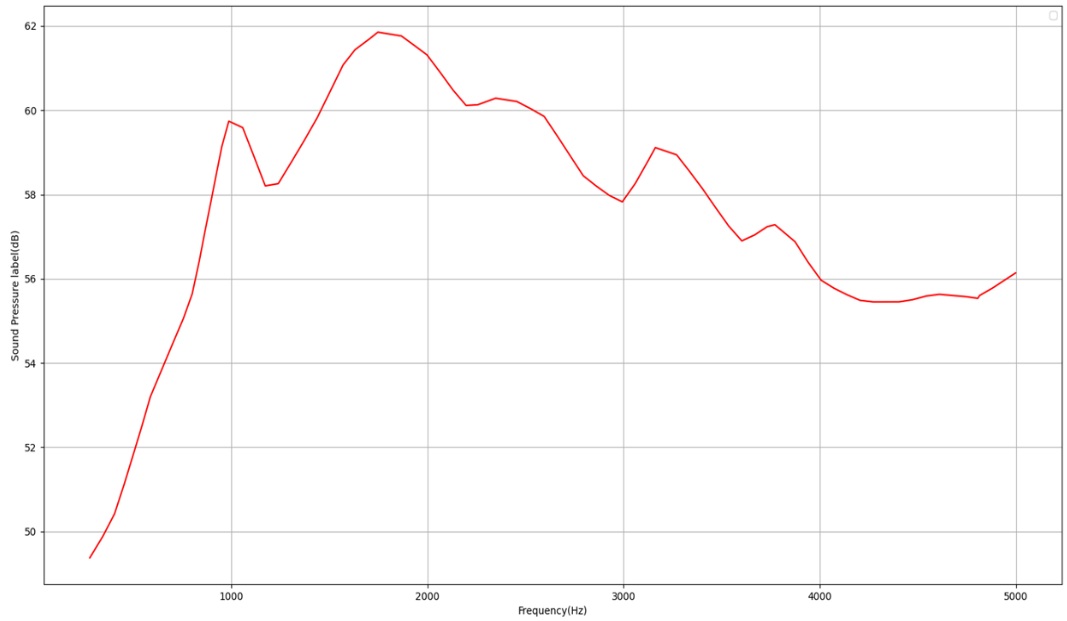
Engine acoustic simulation models are created using the ANSYS workbench, and engine electromagnetic noise is evaluated by using spherical radiation model. The exterior surface of motor construction must be removed and shaped through an enclosure surface, which must then be used to perform relatively close sound computations on a basis domain grid.

The calculating domain is separated into one volume and two sections to meet the needs of acoustic analysis. The internal area is the exterior surface of motor construction provided with vibrations calculation results, and volume is created for the requirements of sound propagation and sound radiation calculations. In addition, the front is necessary for the specification of boundless elements, modeling of open playing conditions, and calculation serve as the sound transmission channel, which is air. The cloud diagrams of (SPL) of two motors with new rotor design arrangement and models produced from simulation calculations.

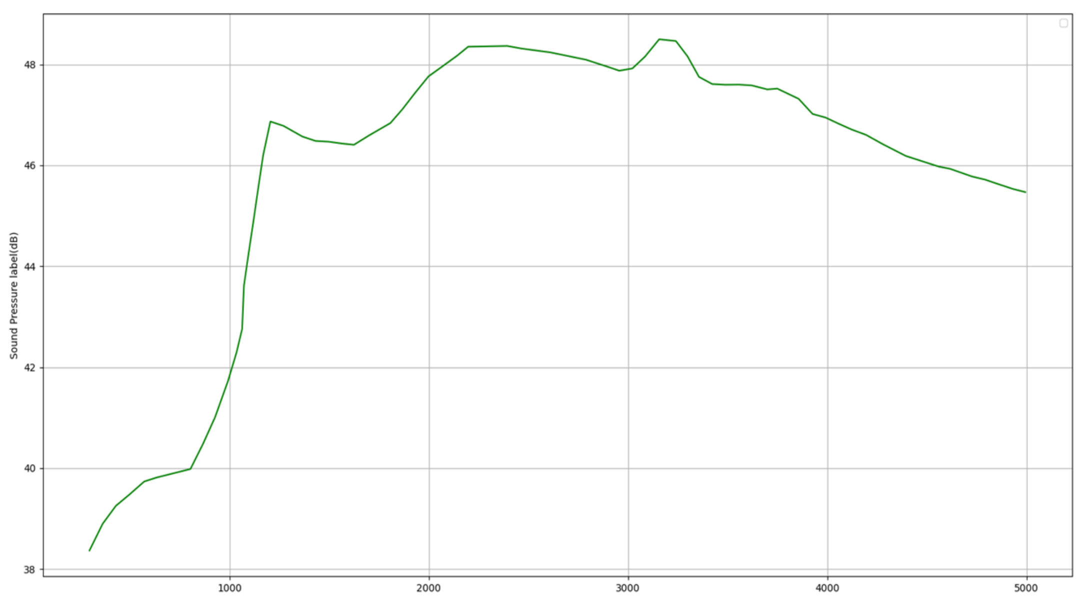
Based on the (SPL) graphs of two analytical results, Fig 5 proves that two rotor proposed design to minimize all variable degrees, the motor's maximum EM noise. The rotor slits, on the other hand, have a little reduction effect, with the highest electromagnetic noise lowered by 4 dB. The "v"-shaped rotor design has a noticeable result, electromagnetic noise was reduced by 9%, from 68 dB prior reduction to 59 dB following reduction, meeting design standards.

Studying the SPL graph of "v"-shaped rotor design motor as well as the model at rated speed, as illustrated in Figure 5, can further prove the ultimate measure in noise amplitude following optimization.

Figure:5 Sound pressure level graph



1



2

1) Indicates SPL VS frequency graph of basic model
2) Indicates SPL VS frequency graph of "V" model

7.Conclusion

This study uses an finite element model and ANSYS workbench finite element analysis platform to investigate the EM noise characteristics of a permanent magnet synchronous motor for electric vehicle driving before and after structural optimization.

The EM radial of the motor is directly related to the EM vibration and noise of the motor, according to theoretical study. The radial air gap EM density determines the motor's EM radial force. The rotor slot optimization strategy can reduce density of motor's EM radial force, hence lowering the EM radial force's amplitude and lowering vibration.

Two distinct rotor designs were compared to design before improvement in order to optimize the magnetic field. The most appropriate rotor slot structure optimization strategy is discovered using the EMF, magnetic field, and acoustic field. When comparing the results in between modification, it is clear that the improved motor reduces effectively motor noise and vibration while preserving EM performance. The SPL is 10.9 percent, which is in line with earlier design guidelines.

9.References

1) P. P. Zhao, and X. B. Du, "Electromagnetic vibration analysis and slot-pole structural optimization for a novel integrated permanent magnet in-wheel motor,", Vol. 13, No. 13, 3488, 2020.

2) Li, J., K. Wang, and F. Li, "Analytical prediction of optimal split ratio of consequent-pole permanent magnet machines," *IET Electric Power Applications*, Vol. 3, No. 12, 365–372, 2017.

3) Zhu, X.-F., W. Hua, and Z.-Z. Wu, "Cogging torque minimisation in FSPM machines by rightangle-based tooth chamfering technique," *IET Electric Power Applications*, Vol. 5, No. 12, 627–634, 2018.

4) Jafarboland, M. and H. B. Farahabadi, "Optimum design of the stator parameters for noise and vibration reduction in BLDC motor," *The Institution of Engineering and Technology*, Vol. 12, No. 9, 1297–1305, 2018.

5) Lee, C.-M., H.-S. Seol, J.-Y. Lee, and D.-W. Kang, "Optimization of vibration and noise characteristics of skewed permanent brushless direct current motor," *IEEE Transactions on Magnetics*, Vol. 53, No. 11, 1–5, 2017.

6) Lin, F., S.-G. Zuo, W.-Z. Deng, and S.-L. Wu, "Reduction of vibration and acoustic noise in permanent magnet synchronous motor by optimizing magnetic forces," *Journal of Sound and Vibration*, Vol. 429, 193–205, 2018.

7) Lecointe, J.-P., B. Cassoret, and J.-F. Brudny, "Distinction of toothing and saturation effects on magnetic noise of induction motors," *Progress In Electromagnetics Research*, Vol. 112, 125–137, 2011.

8 Ma, C.-G., J.-M. Li, H.-C. Zhao, J.-H. Wang, X.-R. Yin, S.-G. Zuo, X.-D. Wu, and H.-F. Lu, "3-D analytical model of armature reaction field of IPMSM with multi-segmented skewed poles andmulti-layered flat wire winding considering current harmonics," *IEEE ACCESS*, Vol. 8, 151116–1511124, 2020.

9 Dong, Q.-C., X.-T. Liu, H.-Z. Qi, C. Sun, and Y.-S. Wang, "Analysis and evaluation of electromagnetic vibration and noise in permanent magnet synchronous motor with rotor step skewing,", Vol. 62, No. 5, 839–848, 2019.

10. Lu, Y.-H. Wang, G. Lei, J.-Z. Zhu, and Y.-G. Guo, "Techniques for reduction of the cogging torque in claw pole machines with SMC cores," *Energies*, Vol. 10, No. 10, 1541, 2017.

11. Chen, M., K.-T. Chau, C. H. T. Lee, and C.-H. Liu, "Design and analysis of a new axial-field magnetic variable gear using pole-changing permanent magnets," *Progress In Electromagnetics Research*, Vol. 153, 23–32, 2015.

12 Nobahari, A., A. Darabo, and A. Hassannia, "Various skewing arrangements and relative position of dual rotor of an axial flux induction motor, modelling and performance evaluation," *IET Electric Power Applications*, Vol. 4, No. 12, 575–580, 2018. 13. Bonthu, S. S. R., T. Bin, and S. Choi, "Optimal torque

ripple reduction technique for outer rotor permanent magnet synchronous reluctance motors," *IEEE Transactions on Energy Conversion*, Vol. 3, No. 33, 1184–1192, 2018.
14. Huang, Y.-H., L.-B. Yan, F. Yang, and W.-J. Zeng, "Research on active disturbance rejection control of hybrid excitation magnetic suspension switched reluctance motor considering noise," *Progress In Electromagnetics Research M*, Vol. 93, 197–207, 2020.
15. Ruba, M., F. Jurca, L. Czumbil, D. D. Micu, C. Martis, A. Polycarpou, and R. Rizzo, "Synchronous reluctance machine geometry optimisation through a genetic algorithm based technique," *IET Electric Power Applications*, Vol. 3, No. 12, 431–438, 2018. 16. Hara, T., T. Ajima, Y. Tanabe, M. Watanabe, K. Hoshino, and K. Oyama, "Analysis of vibration and noise in permanent magnet synchronous motors with distributed winding for the PWM method," *IEEE Transactions on Industry Applications*, Vol. 54, No. 6, 6042–6049, 2018.
17 Rafaq, M. S. and J. W. Jung, "A comprehensive review of state-of-the-art parameter estimation techniques for permanent magnet synchronous motors in wide speed range," *IEEE Transactions on Industrial Informatics*, Vol. 7, No. 16, 4747–4758, 2020.
18. Ramaiah, V. J. and S. Keerthipati, "Hybrid PWM scheme for pole-phase modulation induction motor drive using carrier-based hexagonal and octadecagonal SVPWM," *IEEE Transactions on Industrial Electronics*, Vol. 9, No. 67, 7312–7320, 2020.
19) S. T. Lee, "Development and analysis of interior permanent magnet synchronous motor with field excitation structure", PhD. thesis, University of Tennessee, Knoxville, TN, 2009.
20) J.-J. Lee, S.-O. Kwon, J.-P. Hong, and K.-H. Ha, "Cogging torque analysis of the PMSM for high performance electrical motor considering magnetic anisotropy of electrical steel," World Electric Vehicle Journal, vol. 3, no. 2, pp. 365–369, 2009. vibration prediction of permanent magnet synchronous motor," Journal of Vibroengineering, vol. 20, no. 5, pp. 2225–2236, 2018.
21) Q. Dong, X. Liu, H. Qi, C. Sun, and Y. Wang, "Analysis and evaluation of electromagnetic vibration and noise in permanent magnet synchronous motor with rotor step skewing," Science China Technological Sciences, vol. 62, no. 5, pp. 839–848, 2019.
22) A. K. Putri, S. Rick, D. Franck, and K. Hameyer, "Application of sinusoidal field pole in a permanent-magnet synchronous machine to improve the NVH behavior considering the MTPA and MTPV operation area," IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2280–2288, 2016.
23) L. Zhu, Q. Yang, R. Yan, Y. Li, and W. Yan, "Magnetoelastic numerical analysis of permanent magnet synchronous motor including magnetostriction effects and harmonics," IEEE Transactions on Applied Superconductivity, vol. 24, no. 3, pp. 1–4, 2014.
24) Rick, S., A. K. Putri, D. Frank, and K. Hameyer, "Hybrid acoustic model of electric vehicles:

Force excitation in permanent-magnet synchronous machines," *IEEE Transactions on Industry Applications*, Vol. 52, No. 4, 2979–2987, 2016.