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Investigation on various stator structure towards noise and vibration

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ABSTRACT

This research analyses the noise and vibration characteristics of permanent magnet motors (PMM) with the electromagnetic characteristics, with an emphasis on high-speed motor segmented closed slot stator. The interaction between the stator, rotor, and magnets can cause a vibration that results in the loud sound due to the high magnetic energy. Even if there aren't many vibrations to contend with, the fluctuation of motor vibrations causes more serious harm. The studies covered slotted stator, closed slot stator, and segmented with closed slot stator. The objective is to analyze the cogging torque relation towards vibration and the effect of natural frequency at steady-state behavior of the structure. ANSYS finite element analysis (FEA) is used to generate electromagnetic analysis performance whilst ANSYS mechanical used to simulate the modal and harmonic analysis at the stator tooth tips surface to define the structure when the steady-state condition under vibrational stimulation. Anticipation on this work shows, the lowest cogging torque produce less radiated sound. Thus, the result indicates the cogging torque profiles had good agreement with the equivalent radiated power level (ERPL) waterfall diagram.

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1. INTRODUCTION

The permanent magnet motor has been a popular choice for market players and everyday appliances in this decade. This motor's features include high efficiency, high power density, and a great energy-saving impact [1]. Furthermore, the successful development of high heat resistance, the expansion of high magnetic qualities of rare earth materials such as Neodymium iron boron (NdFeB), and the growth of power electronic components have all helped to enhance the permanent magnet motor (PMM) globally. The research industry is presently attempting to miniaturize motors with high torque, high functionality, and the ability to rotate hundreds of thousands of revolutions per minute. In today's high-speed motor development, the permanent magnet motor with inside rotor topology is quite common [2]–[4].

Despite the advantages listed above, there are also disadvantages of these types of motor. One of the major problems is the noise and vibration back issue. The high magnetic energy during interaction between stator, rotor, and magnets able to yield some vibrations which produce the noisy sound. Even though the vibrations issue is small to counter, but the fluctuation of motor vibrations leads to more severe damage. The electromagnetic vibrations source consists of two types. The types are torque pulsation and the electromagnetic forces. It is crucial to identify the vibrations that originated from electromagnetic sources. Here, these sources consisting of cogging torque existence and the torque ripple formation. The cogging torque is existing due to slotting effect and the magnetic flux interaction that prevent rotor to rotates. This occurs because of circumferential component attractive forces that strive to keep the stator tooth and permanent magnet aligned. Meanwhile, the torque ripple defines as load pulsation generated because of the input current and the EMF harmonics. According to [3]–[7] the vibration profile is enhanced when the harmonic sources is determined. Once the vibration profile improved, the noise characteristics also improved.

The cogging torque reduction approach was described using several techniques in earlier publications [8]–[11]. Previous research focused on developing new rotor and stator modifications to lessen or eliminate cogging. Additionally, a poor saturation effect will result in substantial losses, particularly when a motor operated at a high-speed. In previous articles, the adjustment of the magnet volume has been used to reduce the cogging torque on the rotor side. An ideal high-speed PMM motor must have its stator tooth optimized, especially in the early stages of design. A good stator tooth design is necessary to let as much as a possible path for flux produced by stator windings to flow into the rotor and complete the flux path. The magnetic field which is produced in the machine's air gap is due to the stator component. Extreme heat, winding and iron losses, flux density, and noise problems will all be impacted [12]. The design must also concentrate the flux density into the stator tooth so that it can disseminate over the stator yoke and lessen the saturation effect.

The slot-opening size, the appropriate slot-pole arrangement, and the number of phases all had an impact on the cogging torque of the stator side. The positive result on slot opening sizing has led to the slot-less topology implementation. Based on the slot-less topology the stator is formed as a ring and stacked together with a special glue to shape the structure. The good arrangement of winding is a concern to this topology to protect from overheating. Whilst, the segmented stator core is defined as suitable way to shape the winding arrangement. The advantage of segmented is to reduce the thermal resistance occurs in winding and increase the torque density because the stator slot is fully utilized. The small gap in stator segmented play a vital impact on cogging torque and torque ripple. In the IPM radial motor, the cogging torque magnitude for uniform and non-uniform additional air gap on the segmented stator increases when the gaps increase due to the flux leakage through the tooth tips. The skew method produces effective cogging torque and ineffective for non-uniform stator gaps [13]. The rotor modification on magnet and stator tooth tips shape has resulted in cogging torque reduction and a high percentage of magnet losses. The stator formed as segmented with slotted topology with the modification of magnet circumference to investigate the effect on induce voltage, transient torque, cogging torque, and the torque ripple [14]. Another study that focuses on segmentation stator is discussed by Hong *et al.* [15]. The stator formed segmented with a slotted structure and there are two models evaluated. The first structure is only cut on the stator joint with an overhang structure, Meanwhile, another model involved two segments. The model is cut out on the yoke and bottom stator tooth. The second model assembled using the welding method to replace the epoxy or utilizing adhesive tools. The simulation performed using FEM analysis with an external circuit editor under no-load conditions. As a result, the welding has formed a magnetic closed loop that impacts great core loss [15]. Nevertheless, this study focuses on segmented slotted stator with six slots four pole combination and does not focus on the harmonic response analysis.

Modal analysis is a vital technique for comprehending the structural dynamics of things. This tool is used to analyze the structure of the vibration when applied to the forces. While the harmonic response is an analysis to determine the steady-state response under the load. In harmonic analysis, the equivalent radiated power level (ERPL) can be determined to estimate the radiated structure sound power from the vibrating structural surface. The two-analysis modal and harmonic response analysis are combination tools to strengthen the evidence that cogging torque is one of the sources leading to vibration. The affected surface resulted from the radiated sound power level. Modal and harmonic analysis have heavily influenced the development of the electric motor. The study of harmonic toward electric motor was discovered for diverse types of the electric motor such as switched reluctance motor, induction motor and the permanent magnet motor [16]–[20]. Every component of an electrical motor is considered to reduce vibration and noise. For example, the stator slot number, height of the stator pole, stator yoke thickness and the stator geometry modifications can affect the natural frequency at the same time mitigate the noise and vibrations [21]–[23]. However, the previous literature was focusing the slotted stator structure to analyze. On another point, the electromagnetic sources which produced the noisy sound are limitless to the motor structure. The noise is also produced between sinusoidally driven, and inverter driven. Through the harmonic response analysis, Ahmed *et al.* [24] focused on the healthy operating point of the electric motor to reduce noisy sound. The IPMSM connected with the electronic driver operates under static and dynamic eccentricity conditions. The finding showed that eccentricity influence the operating point as well as the motor vibration.

Here, this work implements the modification of a conventional stator to a segmented stator with a closed slot stator to reduce the cogging torque. A high-speed application is the foundation of the modelling design. The rotor was originally in form of surface-mounted type, but owing to high-speed operation, it converted to interior permanent magnet types. The aim is to justify the relationship between cogging torque and harmonic toward the stator adjustments investigated using the modal analysis and harmonic response. The radiated sound on the impacted surface is presented using the equivalent radiated power level (ERPL) waterfall diagram.

2. BASIC STRUCTURE OF PERMANENT MAGNET MOTOR

This section explained on the process of modeling and design permanent magnet motor (PMM) for high-speed application. The advantages of PMM being such a highly efficient, high-power density, and good control strategy has caused PMM to be a suitable candidate to run the application. Initially, the model designed based on conventional surface mounts permanent magnet (SPM) as in Figure 1. The SPM has a retaining sleeve to resist centrifugal force for high-speed operation. Insufficiency of mechanical strength make it unable to perform for an extended period of time. On the stator side, the existence of a slot opening structure enable it to produce the cogging torque and vibration while maintain high speed rotation. Meanwhile, in coreless motor, the winding that consists of a set of wound coils with no iron core provides lightweight stator without any slot opening. However, it cannot handle heavy loads compared to a cored motor due to heating issues. As the temperature rises, the bonding adhesive that holds the wound coil lost its bond character and the electric motor is prone to fail.

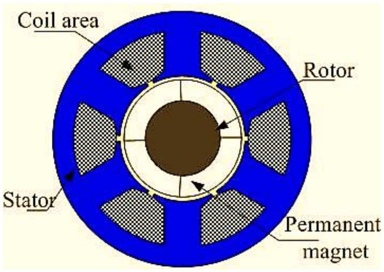


Figure 1. Basic structure of PMM

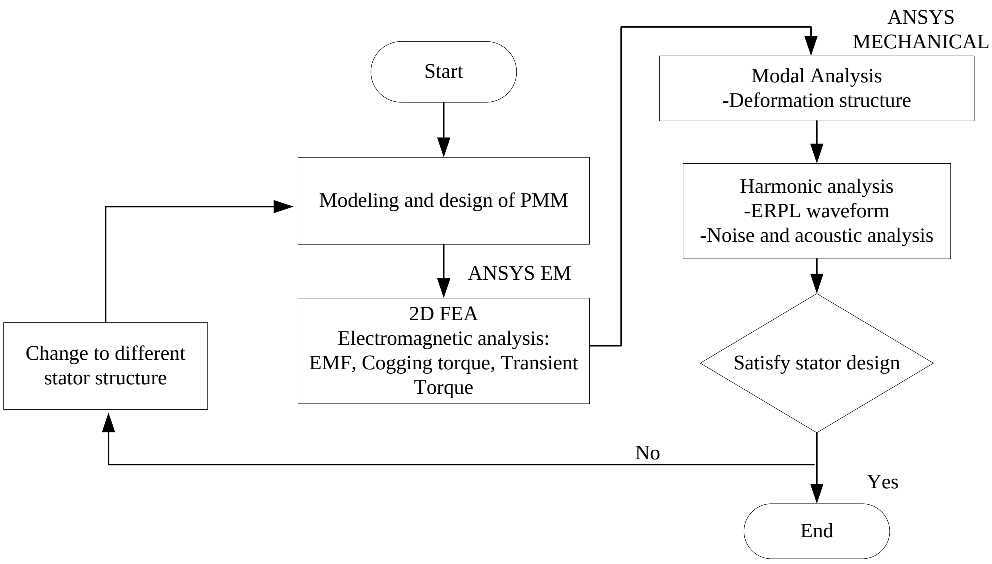
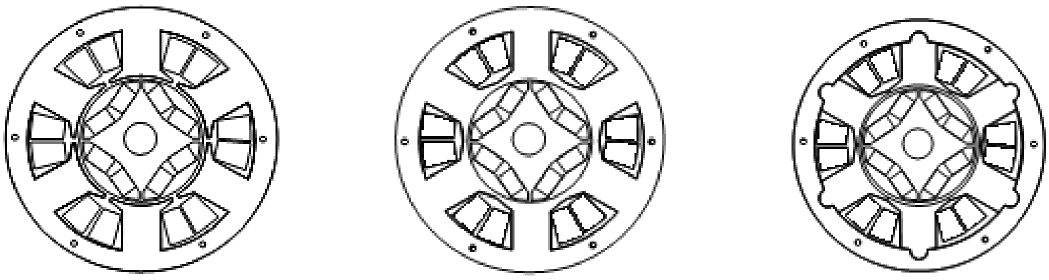


Figure 2. Overall methodology of investigation on various stator structure towards noise and vibration

Therefore, the project work suggested to address issues on slotting effect and the centrifugal forces issues. Figure 2 show the analysis workflow. The stator selection based on the closed slot structure and the IPM rotor is chosen to replace the surface mount rotor. The modeling of different stator structure presented as in Figure 3. Figure 3(a) showed slotted interior permanent magnet motor (SIPM), Figure 3(b) is interior permanent magnet with closed slot (CIPM) and Figure 3(c) is segmented stator with closed slot permanent magnet motor (SPMM). The modeling of stator structure resembling as slot-less topology because this topology able to reduce the cogging torque significantly. To evaluate the performance of the PMM models in term of the electromagnetic analysis, each modeling is examined. This is done to assess the performance of the PMM, including induce voltage and cogging torque.

Furthermore, the modal analysis conducted to define the characteristics of affected structure when the force is enabled to the models. Then, the modal analysis accomplished to predict the radiated sound produce on the involved surface. The findings from the analysis are plotted to define which model is good to fabricate for further work. PMM is modelled using the high-speed application design requirements provided in Table 1. The simulation for all structure has performed in Ansys Maxwell FEM software. The Ansys Maxwell FEM software is used because it able to predict the characteristics of the back EMF and cogging torque [25], [26]. The design requirements, as well as the high-speed parameters, shown in Table 1. The outer diameter is fixed to 84 mm. The model parameters are listed in Table 2. Since the rotor is switched to the IPM topology, the rectangular shape of permanent magnet is chosen. The model had same slot and pole number with a fixed permanent magnet volume of 9600 At due to available size of permanent magnet in laboratory.



(a) (b) (c)

Figure 3. Stator structure: (a) SIPM, (b) CIPM, and (c) SPMM

Table 1. Design specifications

Design specifications	Value
Power, *P* [W]	600
No. phases	3
Rated speed range, N_s [rpm]	30,000
Maximum current, *I* [A]	13

Table 2. Design parameter of stator

Parameter	Value
Stator outer diameter [mm]	84
Stator yoke thickness [mm]	6.5
Slot depth [mm]	13.5
Stator tooth height [mm]	15
Stator tooth width [mm]	12
Slot opening [mm]	1
Stator tip [mm]	0.9
Winding turns per phase, N	20
Air Gap [mm]	1
Stack length [mm]	30

3. ELECTROMAGNETIC ANALYSIS

This section explained on the simulation of the electromagnetics parameter. The research starts with an evaluation of the cogging torque and induce voltage. Finite element analysis (FEA) is used to conduct the analysis using Ansys Maxwell. Equations relating to magnetic vector potential (A), magnetic density (B), and magnetic field intensity are used in the study (H). Static computation is used to calculate the modeling under no load conditions. The simulation is set up to work with three-phase configurations. The model rotates with constant speed in the transient magnetic mode. The rated speed setup is 30,000 rpm. Using parametric analysis, the speed is adjusted linearly every 15,000 rpm until 45,000 rpm to have variation on different speeds. To select an appropriate model, the results are compared. The result computation is calculated with full fraction mode.

In (1) is used to calculate the cogging torque value with Φ_g is air gap flux, while R is air gap reluctance. The induce voltage, ε can be calculated using (2), N is turning number per phase. The nominal speed is set to 30,000 rpm. The speed is varied linear every 15,000 rpm using parametric analysis.

$$T_{cog}=-\frac{1}{2}\Phi_g^2\frac{dR}{d\theta} \quad (1)$$

$$\mathcal{E}=N\frac{d\phi}{dt} \quad (2)$$

– Modal analysis and harmonic analysis

Modal analysis is a tool to define the characteristic a part or structure. It provides an overview of frequency limit of certain system [27]. As previously mentioned, the noise is produced when the resonance occurs between the electromagnetic force and the stator part. The vibration with the great amplitude will occurs once the frequencies of harmonic component of electromagnetics force is closed to the exciting frequencies. Through this study, the load force to calculate the electromagnetic force is enabling to the structure, in this case stator tooth. The certain amplitude and frequency are applied to analyze the limit and the maximum displacement occurs on the stator tooth. The analysis is executed by integrate the model between the electromagnetic analysis with the modal analysis. This is because of the stator part which contribute to the state of resonance. Fixed support is added on the stator bolt. The analysis is setup to natural modes of vibration. The internal frequency is set based on the frequency at which the object is naturally vibrate. Since the PMM design is small, the modal analysis is set to mode, m=0, m=2, and m=4. Every mode has significance deflection pattern corresponding natural frequency.

The noise and vibration are generated from the interaction of the stator and rotor fields. When the radial force frequency matches the fundamental frequency of the structure, resonance occurs [28]. The resonance occurs when the structure forced to vibrate on its natural frequency with the periodic forces as effect of stator and rotor field. The electric motor with higher magnetic loading, such a higher magnetic flux density, tend to produce more noise. It is crucial to establish the frequencies at which the noise will occur. The frequencies at which the radial forces occur can be identified by enabling the forces acting on the stator tooth and conduct the harmonic response analysis. The analysis setup is shown as in Figure 4. Through the analysis, the maxwell stress tensor (MST) is used to calculate the electromagnetic forces around the stator tooth. The system used the virtual forces to estimate the forces around the stator tooth. By using this method, the arcs line along the air gap is integrated using Maxwell Stress Tensor to define the forces. The force is calculated using Maxwell Stress Tensor as in (3) B_r is radial magnetic field, $B_r^{\frac{s}{r}}$ radial stator rotor magnetic field. λ is permeance of material and $F_{mmf}^{\frac{s}{r}}$ magnetomotive force stator and rotor.

$$B_r(\theta,t) = B_r^r(\theta,t) + B_r^s(\theta,t) = \lambda(\theta,t)\left[F_{mmf}^r(\theta,t) + F_{mmf}^s(\theta,t)\right] \quad (3)$$

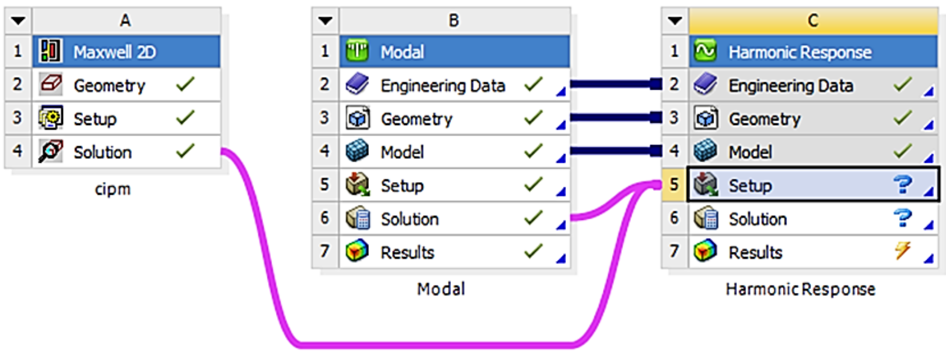


Figure 4. Modal and harmonic response analysis of different stator structure

As the electromagnetic forces is estimated the radial forces frequencies can be determined using the Fourier Transformation Analysis. Here, the vibration is determined when the radial force frequency coincides with the fundamental frequency of the stator tooth. Next, the total deformation on the stator tooth and the harmonic response analysis is evaluated for different modified stator. The parametric analysis is accomplished with multi-speed starting on 15,000 rpm with linear step every 15,000 rpm until 45,000 rpm to capture the radiated spectrogram. The harmonic response analyzed the stator tooth structure and translated to ERPL waveform to present the acoustic sound of structure. The result estimates the radiated structure sound from the vibrating surface. The plotted waveform indicates the area resonance occurred because of the vibration.

4. SIMULATION RESULT AND DISCUSSION

The simulation results were described in this section. The electromagnetic analysis findings make up the first section. The modal analysis makes up the second section. The harmonic response result is the third section, and the comparison of various stators is the fourth.

4.1. Findings of electromagnetic analysis

Based on Figure 5(a), the result shows, the induce voltage profiles of separate set of models are same. SIPM produce sinusoidal waveform profiles. The strong simultaneous torque line stimulates from the patterns of induce voltage profiles. For closed slot, the CIPM has highest EMF value, which is 36 V, while SPMM produce 33 V. Figure 5(b) shows the graph of cogging torque for SPMM, SIPM, and CIPM result. The SIPM model has highest cogging torque due to the slotting effect. For closed model, CIPM has lowest cogging torque. The cogging torque result shows that, the stator without the slot-opening absence able to reduce the cogging torque. This is due to the offset gap is too small, the tendency of rotor to displaced to the higher reluctance is reduced and resulting the low cogging torque.

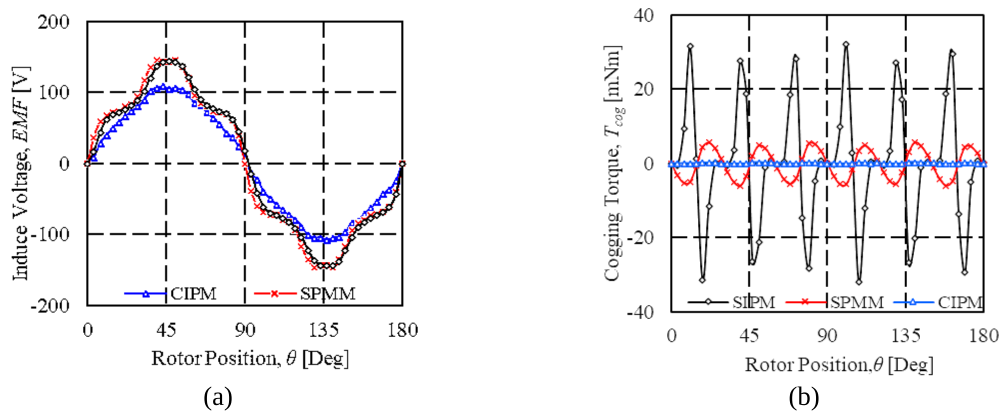


Figure 5. Electromagnetics analysis: (a) induce voltage, and (b) maximum cogging torque

4.2. Findings of modal analysis

Modal analysis was analyzed according to the different stator types. As shown in Figure 6, it shows the characteristics of different stator structure while modal analysis was executed. The analysis focused on the deformation of stator tooth. The findings show, the natural frequencies on the stator tooth for each model increase slightly as the mode increase. The total deformation trend on the stator tooth is fluctuated for all models. SIPM experienced large deformation until 160 mm. The maximum deformation indicates in red marker as maximum point on the left side of stator tooth tip part. The maximum marker showed the stator part experienced a severe bending deformation. The CIPM model is deform about 82.3 mm as in Figure 6(b) with severe deformation occurred on the upper left of stator tooth tip. Finally, the SPMM had small deformation about 2.94 mm with maximum deformation occurred on bottom right of stator part. SIPM and CIPM had severe deformation due to the fixed support of bolt and stator is formed as one part of body. Meanwhile the SPMM, the fixed support of bolt is separated within the stator yoke and stator tooth part. It’s showed that the fixed support of bolt influences the deformation of stator tooth.

4.3. Harmonic response analysis

The radiated sound produced by all model visualized as in waterfall diagram shown in Figure 7. Figure 7(a) shows that SIPM spectrum has reach until 51.1 dB sound of amplitude. Meanwhile, the SPMM sound radiated about 37.3 dB amplitude and CIPM produced about 23 dB sound. The noise sound increased when reach 981 Hz natural frequency as the speed slightly increased for all stator models. From the waterfall diagram, SIPM shows the noisiest sound region compared the other two model. Its show a huge potential vibration occurred on the SIPM stator tooth surface. The radiated sound occurred starting after 52 Hz. Whilst in SPMM the waterfall specifies the sound radiated after 517 Hz followed by the CIPM model the sound is radiated when the frequency reach 981 Hz.

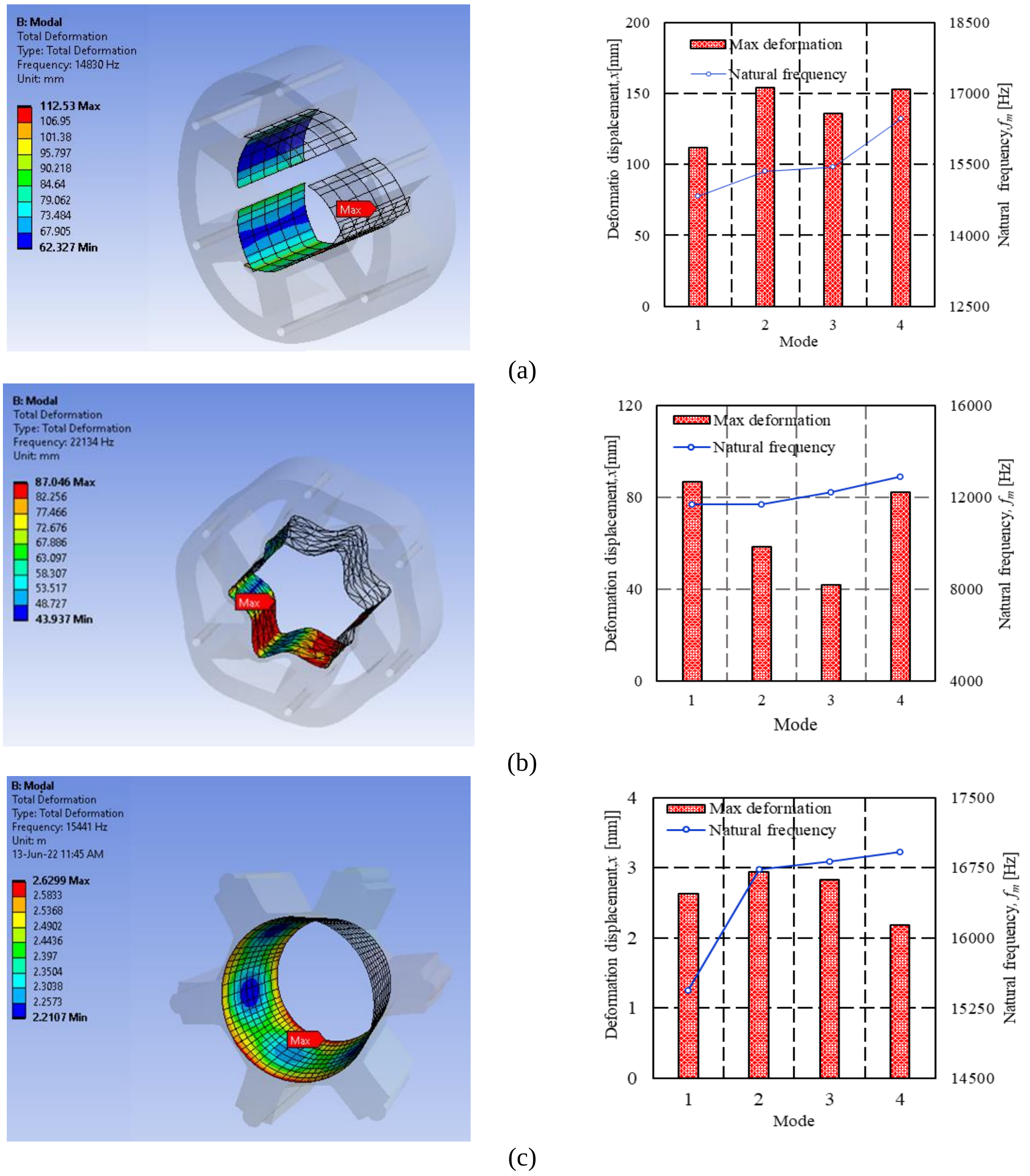
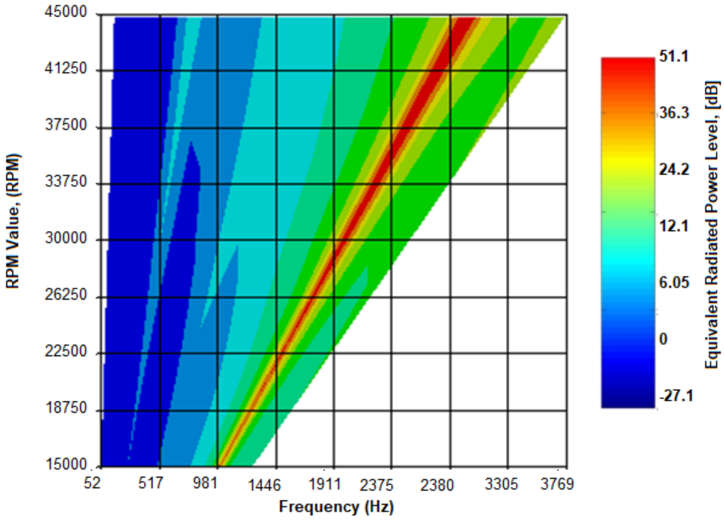


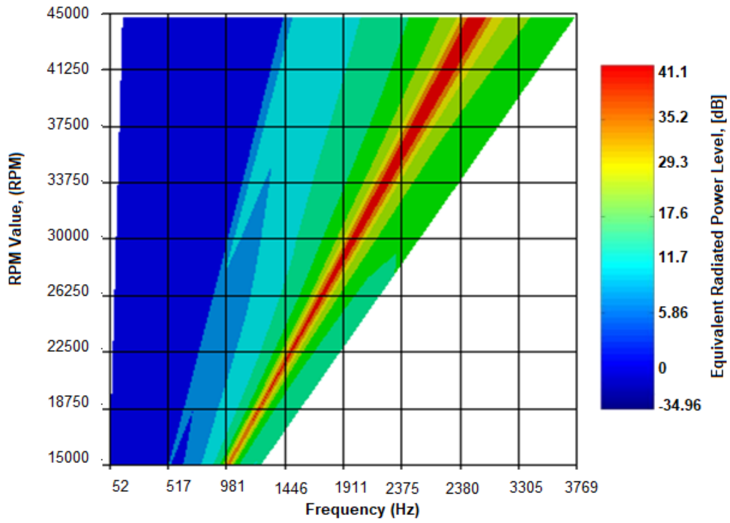
Figure 6. Modal Analysis and total deformation of PMM stator tooth: (a) SIPM (b) CIPM (c) SPMM

4.4. Evaluation of different stator structure

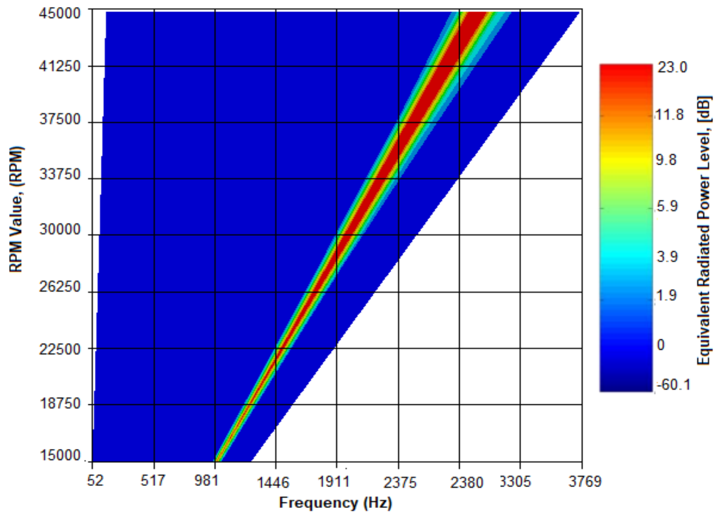
Figure 8 shows the relation between cogging torque and ERPL of different stator structure. As shown in Figure 8(a), the CIPM has lowest cogging torque regarding the structure of the model resembles as closed slot. Thus, there is minimal interaction between the stator slot and rotor. Meanwhile, the SPMM which had closed slot produced 5.6 mNm cogging torque compared to slotted stator which produced about 32 mNm. Figure 8(b) shows the radiated power level that generated when forces is enable and harmonic response is analyzed. The CIPM reach until 18 dB noise amplitude, the SPMM model had 36 dB amplitude noise while SIPM produce until 46 dB noise amplitude at nominal speed. The absence of stator slot generates lowest radiated sound level, compared to the slotted stator. The noise sound level characteristics for all models had good agreement with the cogging torque result. According to the result, the stator structure influences the improvement of the cogging torque as well as the radiated sound level to the surface in this case the stator tooth.



(a)



(b)



(c)

Figure 7. ERPL waterfall diagram of different stator structure: (a) SIPM, (b) SPMM, and (c) CIPM

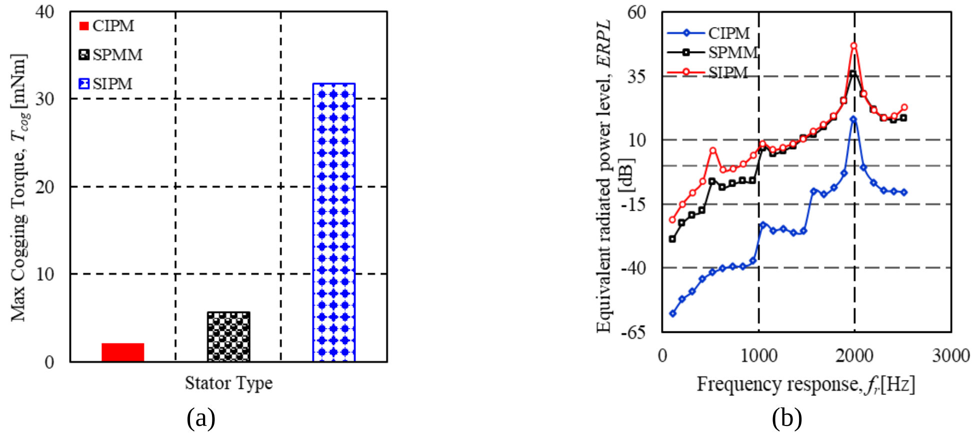


Figure 8. Relation between cogging torque and noise sound of different stator: (a) max cogging torque and (b) ERPL at rated speed

5. CONCLUSION

Based on the simulation result, it can be concluded that the SIPM has high cogging torque due the slotting effect and this model produced cogging torque that led to vibration. The other two models, CIPM and SPMM had potential to reduce the cogging torque due to the absence of slotting effect. But owing to assembly process, for custom made machine, CIPM model required special tools like needle winding machine for winding process. Regarding to the modal analysis its shows that, the SPMM model has lowest deformation when the high natural frequency in electrical component is applied. Since the stator structure is modified from slotted to closed slot part the natural frequencies are affected too.

In conclusion, the aim to study the characteristics of different stator model focusing on the stator tooth is analyzed. The analysis to define the cogging torque relation with the radiated sound level toward the vibration is presented. Through the findings, the modal analysis of stator specifically for stator tooth is the main parameter to shows that the vibration is dependent on the model structure. It shows that the slotted tooth structure has high interactives forces compare than closed slot tooth. As the cogging torque increased the radiated sound level are also increased. The features of radiated sound level are found to be in good agreement with the cogging torque result in this investigation. As a result, this will serve as a baseline for determining the suitable model and assessing the outcomes for a high-speed application.

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