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(54) **Title:** TORQUE RIPPLE REDUCTION IN AC MACHINES

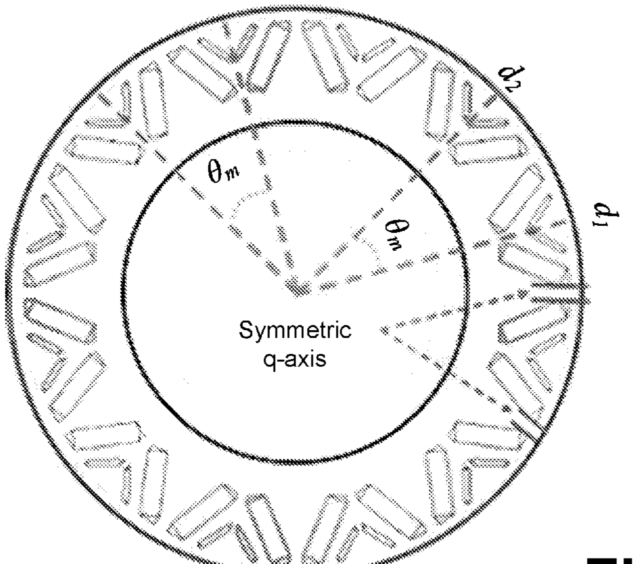

FIG. 2A

(57) **Abstract:** Various examples related to stator and rotor configurations for improvement in torque ripple in AC machines are presented. In one example, a rotor assembly includes a plurality of magnetic pole pairs distributed about a rotor core. Each of the magnetic pole pairs can include a pair of poles separated by a first angular displacement (θ1), and adjacent poles of adjacent magnetic pole pairs are separated by a second angular displacement (θ2) greater than the first angular displacement by a shift angle (θshift = θ2 – θ1). In another example, adjacent poles of the plurality of magnetic poles can include a first pole having a first magnetic arc (α) and a second pole adjacent to the first magnetic pole, the second pole having a second magnetic arc (β). In another example, a motor includes a stator and the rotor assembly such as, e.g., a PM motor, a synchronous reluctance motor, etc.

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TORQUE RIPPLE REDUCTION IN AC MACHINES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to, and the benefit of, co-pending U.S. provisional application entitled "Torque Ripple Reduction, Torque Density Improvement and Efficiency Improvement in AC Machines" having serial no. 62/752,946, filed October 30, 2018, the entirety of which is hereby incorporated by reference.

BACKGROUND

[0002] AC electric machines have multi-teeth stators that house the phase windings of the AC machine in stator slots. The most common type of electric motor is a three-phase motor. Interior permanent magnet (IPM) machines are widely used in electric vehicles, industrial applications, servo applications, electric power steering applications, and home appliances due to its high torque density and high efficiency. However, due to the reaction and reluctance torque, IPM machines are vulnerable to the production of ripple torque if it is not carefully designed. The ripple in torque can be as large as 100% in deep flux weakening and 20% at the maximum torque per ampere (MTPA) point. The salient nature of the rotor introduces high cogging torque that contributes to the torque ripple of the machine as well. However, torque ripple needs to be reduced at a certain level depending on the application.

SUMMARY

[0001] Aspects of the present disclosure are related to stator and rotor configurations for the improvement in torque ripple in AC machines. The disclosed concept can be applied to permanent magnet (PM), synchronous reluctance, PM-assisted synchronous reluctance, induction, transverse flux, and flux switching type rotors, among others.

[0002] In one aspect, among others, a rotor assembly comprises a rotor core; and a plurality of magnetic pole pairs distributed about the rotor core adjacent to an outer surface of the rotor core. Each of the magnetic pole pairs can comprise a pair of poles separated by a first angular displacement (θ_1), and adjacent poles of adjacent magnetic pole pairs are separated by a second angular displacement (θ_2) greater than the first angular displacement by a shift angle ($\theta_{shift} = \theta_2 - \theta_1$). In one or more aspects, the shift angle (θ_{shift}) can be equal to $180/(n{\cdot}P)$, where P is the number of poles distributed about the rotor core, and n can be an order of a cogging torque harmonic or torque ripple harmonic eliminated by the asymmetrical distribution of poles about the rotor core. The plurality of magnetic pole pairs can be formed by permanent magnets mounted in the rotor core.

[0003] In various aspects, the rotor assembly can be mounted in a bar wound stator comprising a stator core comprising winding slots that extend generally radially outward from a rotor air gap; and a set of bar type conductors disposed in adjacent winding slots of the stator core. In some aspects, the rotor assembly can be a permanent magnet (PM) rotor, a synchronous reluctance rotor, a PM-assisted synchronous reluctance rotor, an induction rotor, a transverse flux rotor or a flux switching type rotor.

[0004] In another aspect, a rotor assembly comprises a rotor core; and a plurality of magnetic poles distributed about the rotor core adjacent to an outer surface of the rotor core. Adjacent poles of the plurality of magnetic poles can comprise a first pole having a first magnetic arc (α) and a second pole adjacent to the first magnetic pole, the second pole having a second magnetic arc (β). In one or more aspects, the first pole can comprise symmetrically distributed permanent magnets and the second pole can comprise asymmetrically distributed permanent magnets with an angular shift between magnets on one side. the angular shift (θ) can be equal to $180/(2n{\cdot}P)$, where P is the number of poles distributed about the rotor core, and n is an order of a ripple harmonic eliminated by the asymmetrically distributed permanent magnets such that the second magnetic arc is $\beta = \beta_1 + \beta_2$, and $\beta_1 = \beta_2 + \theta$. In various aspects, the rotor assembly can be a permanent magnet (PM) rotor, a synchronous reluctance rotor, a PM-assisted synchronous reluctance rotor, an induction rotor, a transverse flux rotor, or a flux switching type rotor. The rotor assembly can be mounted in a stator.

[0005] In another aspect, a motor comprises a stator and the rotor assembly. In one or more aspects, the rotor can be a permanent magnet (PM) rotor. The PM rotor can be an interior PM rotor. The stator can be a bar wound stator or other appropriately wound stator. The motor can be a permanent magnet (PM) motor, a synchronous reluctance motor, a PM-assisted synchronous reluctance motor, an induction motor, a transverse flux motor, a flux switching type motor, etc.

[0006] Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims. In addition, all optional and preferred features and modifications of the described embodiments are usable in all aspects of the disclosure taught herein. Furthermore, the individual features of the dependent claims, as well as all optional and preferred features and modifications of the described embodiments are combinable and interchangeable with one another.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0008] FIG. 1A illustrates an example of an airgap flux density spectrum of an IPM machine, in accordance with various embodiments of the present disclosure.

[0009] FIGS. 1B and 1C illustrate an example of the torque wave and corresponding spectrum of the IPM machine of FIG. 1A, in accordance with various embodiments of the present disclosure.

[0010] FIGS. 2A and 2B illustrate an example of the asymmetric concept for ripple reduction in an IPM machine, in accordance with various embodiments of the present disclosure.

[0011] FIG. 3 is a flow diagram illustrating an example of a method for determining an asymmetric rotor design for an IPM machine, in accordance with various embodiments of the present disclosure.

[0012] FIGS. 4A-4C illustrate examples of evaluation results of the IPM machine model of FIG. 2B with respect to base and skewed machine models, in accordance with various embodiments of the present disclosure.

[0013] FIG. 5 illustrates an example of a two-dimensional operational mapping of the IPM machine model of FIG. 2B, in accordance with various embodiments of the present disclosure.

[0014] FIG. 6 illustrates a comparison of cogging torque of the machine models, in accordance with various embodiments of the present disclosure.

[0015] FIGS. 7A-7C illustrate examples of resultant tooth force distribution at a given rotor position, in accordance with various embodiments of the present disclosure.

[0016] FIG. 8 is a schematic diagram illustrating an example of the shift between consecutive poles in a rotor, in accordance with various embodiments of the present disclosure.

[0017] FIGS. 9A-9D illustrate an example of a stator bar winding with an 8-conductor/slot design and its back EMF, in accordance with various embodiments of the present disclosure.

[0018] FIGS. 10A-10C illustrate an example of the stator bar winding and its back EMF with an asymmetric rotor design, in accordance with various embodiments of the present disclosure.

[0019] FIGS. 11A-11G illustrate examples of the stator bar winding back EMF with four and two parallel path connections, in accordance with various embodiments of the present disclosure.

[0020] FIGS. 12A-12E illustrate an example of a winding diagram for a 16 bar per phase, four parallel path stator winding, in accordance with various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0021] Disclosed herein are various examples related to stator and rotor configurations for the reduction in torque ripple. Torque ripple reduction methods have been considered, but often add extra complex manufacturing steps and a burden of extensive optimization. Torque ripple minimization strategies can include skewing of rotor or stator in the axial direction, which is effective in canceling cogging torque or unwanted torque ripple. However, skewing adds manufacturing complexity and increases the cost as well. It can also be ineffective when a stator is highly saturated. It has been shown that an odd number of stator slots per pole pair can effectively reduce the ripple torque of the machine.

[0022] An asymmetric V-shape rotor may also be used to reduce cogging torque along with ripple reduction. However, the asymmetry uses different magnet widths in a single V-shape with extensive optimization to find out the optimum widths of the magnets. Moreover, the effect of this asymmetry in the radial force has not been considered. It also decreases the average torque by more than 3% and adds extra manufacturing steps. Axial pole shaping may also be used to reduce the ripple torque by more than 50% at an expense of 9% average torque reduction. However, PM width variations in the axial direction will increase the number of magnet pieces in a machine compared to the regular interior permanent magnet (IPM) machines. Barrier shifting may also reduce the ripple of a synchronous reluctance machine where consecutive poles are having different barrier angle. Pole-pole variation can be used in a double V-shape rotor to reduce the ripple in an IPM machine. Other methods like pole shaping, notches on the rotor surface, and unequal rotor outer diameter may also be considered for the reduction of the ripple.

[0023] A novel method to reduce the torque ripple and cogging torque is disclosed that can reduce the torque ripple by a substantial amount without adding any manufacturing complexity. The disclosed method can eliminate the requirement of step skewing and can produce significant impact on manufacturing cost reduction. The full rotor stack can be assembled in a single process. To eliminate n-th order harmonics from cogging torque or torque ripple, the angular shift in the magnets can be given as theta_shift =180/nP, where P is the pole number, and theta_shift represents the mechanical shifting angle. This method can reduce the ripple and cogging torque by a substantial amount with a negligible reduction in average torque. This method is applicable for both stranded wound and bar wound stators.

[0024] This method can be applied to all rotor topologies including but not limited to single V, double V, spoke type, surface PM, U type, Delta type. A careful connection of the parallel paths can reduce the possibility of circulating currents due to the asymmetry in the magnet positions. This method is applicable for all motor topologies including but not limited to the permanent magnet synchronous machine, synchronous machine, reluctance machine, and induction machine for both inner and outer rotor configuration.

[0025] Another method to reduce the torque ripple is also disclosed that can reduce the torque ripple by a substantial amount without adding any manufacturing complexity. This method can eliminate the need for step skewing. In this method, the magnet arc of the consecutive poles will be beta_m +theta, beta_m and this will repeat for the whole machine. To eliminate n-th order harmonic from ripple, the theta can be given as 2*theta,=180/nP, where P is the pole number, and theta represents a mechanical angle. This method can reduce the ripple and cogging torque by a substantial amount without reducing the average torque of the machine whereas in conventional ripple minimization technique, average torque is reduced by 3-4%.

[0026] In this disclosure, a ripple reduction method is presented for IPM machines using asymmetry in the $q-$ axis of the rotor. A design methodology to achieve low ripple in IPM machines based on a simple analytical equation to circumvent the need for extensive optimization is proposed and validated using 2D-FEA. The performance of the disclosed method is compared with a base model and a skewed model. The manufacturing issues and physical limitations of the presented concept are addressed. Effect on the radial forces or vibration mode order of this asymmetry is also examined. Application of the disclosed method in an IPM machine can reduce the torque ripple by 70% along with 65% cogging torque reduction at the cost of 3-4% average torque reduction.

Torque Ripple in Regular Interior Permanent Magnet Machines (IPM)

[0027] Torque ripple in IPM machines may be attributed to the interaction of the stator MMF harmonics $f_{s,h}$ and the rotor MMF harmonics $f_{r,h}$. The ripple of an IPM machine can be predicted using the following,

$$T_{ripple} = \frac{P\mu_O R_g L\pi}{2g} \sum_{h=6i\mp1}(hf_{s,h}f_{r,h}\sin((h\mp1)\omega_e t \pm \gamma), \ i = 1,2,3 \ldots \quad (1)$$

The stator MMF harmonics $f_{s,h}$ multiplied with the harmonics of order h interact with the rotor harmonics $f_{r,h}$ to produce the ripple. Therefore, the higher order stator harmonics can contribute disproportionately to the torque ripple. Stator MMF has the dominant harmonics of order $h = i \cdot n_s \mp 1$, where n_s is the slot/pole-pair other than the fundamental component.

[0028] However, the stator has also other odd order harmonics not equal to multiples of three. The rotor MMF contains odd-order harmonics and does not have any even order harmonics since it is even-symmetric about the d −axis and odd-symmetric about the q −axis. Therefore, the torque wave of an IPM machine will contain all the harmonics of multiples of six as in equation (1). The dominant unwanted ripple harmonic will be equal to n_s (slot/pole-pair).

[0029] A regular IPM machine can be designed for the specifications shown in Table I (below) with the objective of maximizing the torque density and minimizing the ripple. A double V-shape rotor with a full pitched stator winding is considered. The spectrum of the airgap flux density due to the rotor excitation is shown in FIG. 1A at a fixed time instant. It contains all the odd order harmonics. The spectrum of airgap flux density due to the stator excitation is shown in FIG. 1A, and contains the fundamental component along with dominant harmonics of $i \cdot n_s \pm 1$ (11^{th}, 13^{th} as the slot per pole pair is 12). The torque wave of this regular IPM design is shown in FIG. 1B for a one-sixth electrical cycle at peak current in the maximum torque per ampere (MTPA) point. The corresponding spectrum in FIG. 1C shows that the dominant order harmonics are multiples of 12, which is related with the slot/pole-pair.

Table I: Specifications	
Diameter (mm)	204
Length (mm), L	65
Slot, Q	72
Pole, P	12
I_{peak}(A, rms)	400
P_{peak}	60 kW
Rotor radius, R_g(mm)	70

Ripple Reduction

[0030] FIG. 2A shows a regular IPM machine with double V-type barriers where magnet axes are equally spaced, and the $q-$ axis having equal angular span or magnet symmetry. In the disclosed concept, the axis of a magnet pole (d_1) can be shifted by $\theta_{shift}/2$ in the clockwise direction (d_1') and the neighboring pole axis by the same angle in opposite direction as illustrated in FIG. 2B. As a result, half of the $q-$ axes will become smaller while the other half become larger which can be termed as a magnetic-axis asymmetry in the rotor as shown in FIG. 2B. Therefore, magnet axes of half of the poles can be shifted by $\theta_m + \theta_{shift}$ and the remaining poles can be shifted by $\theta_m - \theta_{shift}$. The disclosed asmmetry does not add any extra manufacturing steps compared to the regular step skewing or axial pole shaping. It only changes the position of the magnets without changing the magnets. This can be easily achieved by lamination design of the rotor. Magnets of each of the pole are the same as that of a conventional design which keeps the number of magnet pieces the same. In a conventional skewing method, segmentation and shifting of the magnets are produced by complex manufacturing steps, increasing the number of magnet pieces, and finally, increasing the overall manufacturing cost. The step skewing method also reduces the average torque.

[0031] The magnitude of the shift angle depends on the unwanted torque harmonics being targeted. As described, the unwanted torque harmonics are multiples of six. Therefore, to cancel an unwanted dominant torque harmonic h from the torque, the shift angle can be calculated from:

$$\theta_{shift} = \frac{180}{h*p}, \qquad (2)$$

where p is the pole-pair of the machine. Moreover, the integer slot/pole ratio of IPM machines have a cogging period equal to the slot-pitch. Therefore, both the torque ripple and the cogging torque can be substantially reduced by adopting this method in integer slot/pole ratio machine.

[0032] Referring to FIG. 3, shown in an example of a design method based on the disclosed concept. Beginning at 303, a regular machine (with a symmetric rotor) can be designed to achieve the target performance without considering the torque ripple constraints. The unwanted torque harmonic (h) can then be determined at 306 using, e.g., a Fast Fourier Transform (FFT) of the torque wave that is related with the slot/pole pair. The disclosed asymmetric concept can then be applied at 306 on the regular design to reduce the torque ripple. At 309, the ripple performance can be verified. For example, an FEA validation can be done on the updated design. The output of the validation of the asymmetric rotor design is illustrated in the FEA validation at 309. However, the side effects of the disclosed asymmetric concept are a reduction of average torque and periodicity of the machine. The change in periodicity can have a direct effect in radial force of the machine that will be discussed.

Performance Comparison

[0033] To validate the disclosed concept and compare it with the other methods, a double V-type IPM model was developed using 2D-FEA. All the models have the same dimensional constraints, magnet volume, current density, and fill factor. To assess the effectiveness of the asymmetric rotor design, the torque ripple was compared at different loading conditions to consider the saturation effect. The specification of the designed machine is shown in Table I (above). A 12-pole/72-slot IPM machine was considered for the evaluation.

[0034] *Comparison of Electromagnetic Torque.* A three-phase sinusoidal current was fed into the machine model to predict the torque performance. The torque output at peak load condition is illustrated in FIG. 4A. The dominant torque harmonic of the base model is 12th order as shown in FIG. 4B. Therefore, the shift angle to cancel the 12-order harmonic is 2.5-degrees (mechanical) per equation (2). Applying the angular adjustment of the disclosed method, the peak-peak torque ripple is reduced from about 13% to about 4% at the expense of about 4% average torque reduction. The resultant torque spectra is shown in FIG. 4B. It can be seen that the 12th order is substantially reduced for the disclosed (proposed) concept. However, the application of the axial two-step ($2.5°$) skewing reduced the torque ripple from 13% to 6.5% at the expense of 3% average torque reduction. Additionally, two-step skewing results in an extra manufacturing step. The torque performance at the reduced load is compared in Table II (below) for all the models. It can be seen that the asymmetric concept substantially reduces the torque ripple. Therefore, the presented concept can be effective even under highly saturated conditions. The asymmetric rotor design results in a better or similar ripple for the same or a little bit higher average torque reduction without adding any extra manufacturing step compared to the axial step skewing method.

Table II: Performance comparison at 50%I_s

Parameters	Base Model	Proposed	Skewed
T_{avg}	105	102	102
$Ripple$ (%)	14.00	4.00	6.50

[0035] The effect of the shift angle (θ_{shift}) on torque ripple is shown in FIG. 4C. The minimum ripple occurs at the analytically predicted shift angle of $2.5°$. Therefore, the disclosed methodology is simple and can achieve a very low torque ripple without the need for extensive optimization. This can reduce the computational time during the design stage. However, there is a geometrical limit on the shift angle, which depends on the available space in the $q-$ axis of the regular design. After the limit is exceeded, the neighboring poles may touch each other and result in an invalid geometry.

[0036] The presented concept can reduce the torque ripple in all possible operating points which is shown in the mapped $i_d - i_q$ plane in FIG. 5. The peak-peak ripple can be as low as 2% around the base speed and as high as 12% in deep flux weakening at a very light load. During deep flux weakening, phase current can introduce more harmonics in the airgap flux and increase the ripple of the machine. However, the disclosed asymmetric concept can reduce the torque ripple in all the operating points compared to the base model and keep the ripple less than 5% in most of the points. The MTPA trajectory is illustrated by the dotted line, and the solid red lines represent the phase current of the machine.

[0037] *Cogging Torque*. The mechanical period of cogging torque depends on the $LCM(slot,\ pole)$, which is $\frac{360}{LCM(slot,\ pole)}$. For the 12-pole/72-slot design, $\frac{360}{LCM(slot,\ pole)} = \frac{360}{72} = 5$ degree. The dominant cogging harmonic is the $\frac{LCM(slot,\ pole)}{Pole-pair} = \frac{72}{6} = 12^{th}$ order, which coincides with the unwanted torque harmonic. Therefore, cancellation of the torque harmonic will reduce the cogging torque as well. FIG. 6 compares the cogging torque of the three models. The disclosed asymmetric method reduces the cogging torque by 65% $(\pm 0.7\ Nm)$ of the base model. The 12th order harmonic is substantially reduced and the 24th order becomes the dominant one. The skewing method also has similar cogging performance.

[0038] *Radial Forces*. Induced electromagnetic radial forces on the stator teeth can create core deformation and stress the mechanical system, which may create noise and vibration in the system. Airgap stresses can be evaluated using a Maxwell stress sensor,

$$f_r(t,\theta) = (B_r(t,\theta)^2 - B_t(t,\theta))/2\mu_o,$$

$$f_t(t,\theta) = (B_r(t,\theta)B_n(t,\theta))/\mu_o, \tag{3}$$

where $B_r(t,\theta)$ and $B_t(t,\theta)$ are the radial and tangential airgap flux density. The resultant tooth force distribution at a given rotor position is shown in FIGS. 7A and 7B for the base model and the asymmetric model, respectively. Moreover, generally, the fundamental component of tooth force distribution is the dominant vibration mode (m) order of the radial force. Core deformation is inversely proportional to the fourth power of mode order m. Therefore, reduction in the mode order (m) increases the core deformation and may result in higher unwanted acoustic noise. The mode orders of radial forces of stator teeth between the presented and base models are shown in FIG. 7C for comparison. Even though the asymmetric concept substantially reduces the torque ripple, it introduces a lower order vibration mode in the system. In this case, the base model has only the 12th order mode; however, the disclosed model has a dominant 12th order along with a weak 6th order mode. However, the 6th order mode is not that problematic compared to 2nd or 4th orders. Generally, any asymmetry in the rotor design will introduce a lower order mode. Although a weak low order mode has been introduced, it can be addressed during the design stage by selecting appropriate slot/pole combination or by increasing the mass of the stator yoke.

[0039] This disclosure has presented a method for asymmetric magnet placement within a rotor to reduce torque ripple. The disclosed methodology incudes eliminating the n-th order harmonic by implementing a shift angle as provided in equation (2). The shift angle (θ_{shift}) is implemented relative to asymmetrically placed rotor magnets, and can improve torque ripple without an increase in manufacturing costs and/or complexity. FIG. 8 illustrates an example of the shift between consecutive poles. FIG. 8 shows the different magnet arc of the consecutive poles (α, β), where $\beta_1 = \beta_2 + \theta_{shift}$. The interaction of reluctance torque and magnet torque can reduce the torque ripple and make the torque constant. The method can be effective at different load levels.

[0040] In bar windings, the windings are not randomly placed and due to leakage, each bar conductor experiences a different flux linkage compared to the other bar conductors. The flux linkage pattern depends on the bar locations, and this can create issues with circulating currents when parallel connections are desired. The rotor asymmetry can further complicate the process of parallel connections. Consider an 8-conductor/slot design, as shown in FIG. 9A. Generally a layer 1 bar is connected with a layer 5 bar in another slot. So the bars with a certain layer number are connected to bars of an inner layer at the next pole.

[0041] FIG. 9B illustrates the normalized back EMFs for the individual 16 bar conductors shown in FIG. 9A. The phase shifted back EMFs are clearly visible in the time domain plot of FIG. 9B. Most of the back EMF are in phase and thus overlap. The bar charts of FIGS. 9C and 9D show the harmonic magnitude and phase contribution for the first five orders. The fundamental magnitude was removed for clarity. The harmonic contributions clearly dictates two separate groups of back EMF. When a parallel connection is desired, proper selection of bars can ensure a similar back EMF profile for parallel windings. Since there are two groups for the 16 bars, up to 8 parallel connections are possible with this setting (no asymmetry). Evenly sharing the EMF between the two groups can avoid circulating currents.

[0042] FIG. 10A illustrates the normalized back EMFs for the bar conductors of FIG. 9A with an asymmetric rotor design as disclosed. Introducing asymmetric magnets in the rotor creates four groups instead of two. The bar charts of FIGS. 10B and 10C show the harmonic magnitude and phase contribution for the first five orders, with the fundamental magnitude removed. The back EMF harmonics have similar harmonic magnitude contribution but the phase shifting creates four groups. Additional care can be taken with the parallel connections to avoid circulating currents. Some degrees of freedom are removed from the connection strategy. But by observing the phase contribution, it is evident that up to 4 parallel connections are possible due to the four groups.

[0043] FIG. 11A illustrates an example of a connection strategy for four parallel paths with the bar numbers associated with each group. With rotor asymmetry, four parallel paths are the maximum allowable for the 16 bar/phase system of FIG. 9A. The harmonic contribution for the four back EMFs were found to be identical, ensuring no circulating current. FIG. 11B illustrates the normalized back EMFs for the four parallel paths with the asymmetric rotor design, and the bar charts of FIGS. 11C and 11D show the harmonic magnitude and phase contribution. Two parallel paths can be achieved by simply selecting any two and connecting them in series. FIG. 11E illustrates the normalized back EMFs for two parallel paths with the asymmetric rotor design, and the bar charts of FIGS. 11F and 11G show the harmonic magnitude and phase contribution.

[0044] FIGS. 12A-12E illustrate an example of a winding diagram for the 16 bar per phase configuration of FIG. 9A. FIG. 12A illustrates bar conductor numbering for phase U occupancy in adjacent slots. In the example of FIG. 12A, phase U occupies all 8 bars of slot 3 and 4 bars in adjacent slots 2 and 4. The series connections can be made by an appropriate bus bar connector. FIG. 12B shows the winding diagram for phase U in slots 2, 7, 14, 19, 26, 31, 38 and 43 with a coil span of 5 on the crown end and 7 on the weld end. FIG. 12C shows the winding diagram for phase U in slots 3, 8, 15, 20, 27, 32, 39 and 44, FIG. 12D shows the winding diagram for phase U in slots 3, 8, 15, 20, 27, 32, 39 and 44, and FIG. 12E shows the winding diagram for phase U in slots 4, 9, 16, 21, 28, 35, 40 and 47.

[0045] A new torque-ripple reduction method for an IPM machine is shown using asymmetry in the $q-$ axis of the rotor. A simple design methodology can achieve low ripple based on analytical equation was developed and validated using 2D-FEA. The application of the disclosed method in a regular IPM machine shows a substantial reduction of the unwanted torque harmonics by as much as 90%. The results showed that it could reduce the torque ripple by 70% of a base model at an expense of 3-4% average torque reduction. The concept can achieve better or similar ripple performance at the expense of similar average torque reduction compared to an axial step skewing without adding any extra manufacturing step. It also reduces the cogging torque by about 65% compared to the base model, along with the reduction of the peak-peak torque ripple. The disclosed concept can be applied to a wide range of machines such as, e.g., a permanent magnet (PM) motor, a synchronous reluctance motor, a PM-assisted synchronous reluctance motor, an induction motor, a transverse flux motor, or a flux switching type motor. Advantages can include, but are not limited to, reduction in the torque ripple of AC machines by a substantial amount, without adding manufacturing complexity and cost compared to the other existing ripple minimization techniques, reduction in cogging torque, and sinusoidal back EMF.

[0046] It should be emphasized that the described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

[0047] It should be noted that ratios, concentrations, amounts, and other numerical data may be expressed herein in a range format. It is to be understood that such a range format is used for convenience and brevity, and thus, should be interpreted in a flexible manner to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. To illustrate, a concentration range of “about 0.1% to about 5%” should be interpreted to include not only the explicitly recited concentration of about 0.1 wt% to about 5 wt%, but also include individual concentrations (*e.g.*, 1%, 2%, 3%, and 4%) and the sub-ranges (*e.g.*, 0.5%, 1.1%, 2.2%, 3.3%, and 4.4%) within the indicated range. The term “about” can include traditional rounding according to significant figures of numerical values. In addition, the phrase “about ‘x’ to ‘y’” includes “about ‘x’ to about ‘y’”.

CLAIMS

Therefore, at least the following is claimed:

1. A rotor assembly, comprising:

a rotor core; and

a plurality of magnetic pole pairs distributed about the rotor core adjacent to an outer surface of the rotor core, where each of the magnetic pole pairs comprise a pair of poles separated by a first angular displacement (θ_1), and adjacent poles of adjacent magnetic pole pairs are separated by a second angular displacement (θ_2) greater than the first angular displacement by a shift angle ($\theta_{shift} = \theta_2 - \theta_1$).

2. The rotor assembly of claim 1, wherein the shift angle (θ_{shift}) is equal to $180/(n \cdot P)$, where P is the number of poles distributed about the rotor core, and n is an order of a cogging torque harmonic or torque ripple harmonic eliminated by the asymmetrical distribution of poles about the rotor core.

3. The rotor assembly of any of claims 1 and 2, wherein the plurality of magnetic pole pairs are formed by permanent magnets mounted in the rotor core.

4. The rotor assembly of any of claims 1-3, wherein the rotor assembly is mounted in a bar wound stator comprising:

a stator core comprising winding slots that extend generally radially outward from a rotor air gap; and

a set of bar type conductors disposed in adjacent winding slots of the stator core.

5. The rotor assembly of any of claims 1-4, wherein the rotor assembly is a permanent magnet (PM) rotor, a synchronous reluctance rotor, a PM-assisted synchronous

reluctance rotor, an induction rotor, a transverse flux rotor, or a flux switching type rotor.

6. A rotor assembly, comprising:

a rotor core; and

a plurality of magnetic poles distributed about the rotor core adjacent to an outer surface of the rotor core, where adjacent poles of the plurality of magnetic poles comprise a first pole having a first magnetic arc (α) and a second pole adjacent to the first magnetic pole, the second pole having a second magnetic arc (β).

7. The rotor assembly of claim 6, wherein the first pole comprises symmetrically distributed permanent magnets and the second pole comprises asymmetrically distributed permanent magnets with an angular shift between magnets on one side.

8. The rotor assembly of claim 7, wherein the angular shift (θ) is equal to $180/(2n{\cdot}P)$, where P is the number of poles distributed about the rotor core, and n is an order of a ripple harmonic eliminated by the asymmetrically distributed permanent magnets such that the second magnetic arc is $\beta = \beta_1 + \beta_2$, and $\beta_1 = \beta_2 + \theta$.

9. The rotor assembly of any of claims 6-8, wherein the rotor assembly is a permanent magnet (PM) rotor, a synchronous reluctance rotor, a PM-assisted synchronous reluctance rotor, an induction rotor, a transverse flux rotor, or a flux switching type rotor.

10. The rotor assembly of any of claims 6-9, wherein the rotor assembly is mounted in a stator.

11. A motor, comprising:

    a stator; and

    the rotor assembly of any of claims 1-3 and 6-8.

12. The motor of claim 11, wherein the rotor is a permanent magnet (PM) rotor.

13. The motor of claim 12, wherein the PM rotor is an interior PM rotor.

14. The motor of any of claims 11-13, wherein the stator is a bar wound stator.

15. The rotor assembly of any of claims 10-14, wherein the motor is a permanent magnet (PM) motor, a synchronous reluctance motor, a PM-assisted synchronous reluctance motor, an induction motor, a transverse flux motor, or a flux switching type motor.

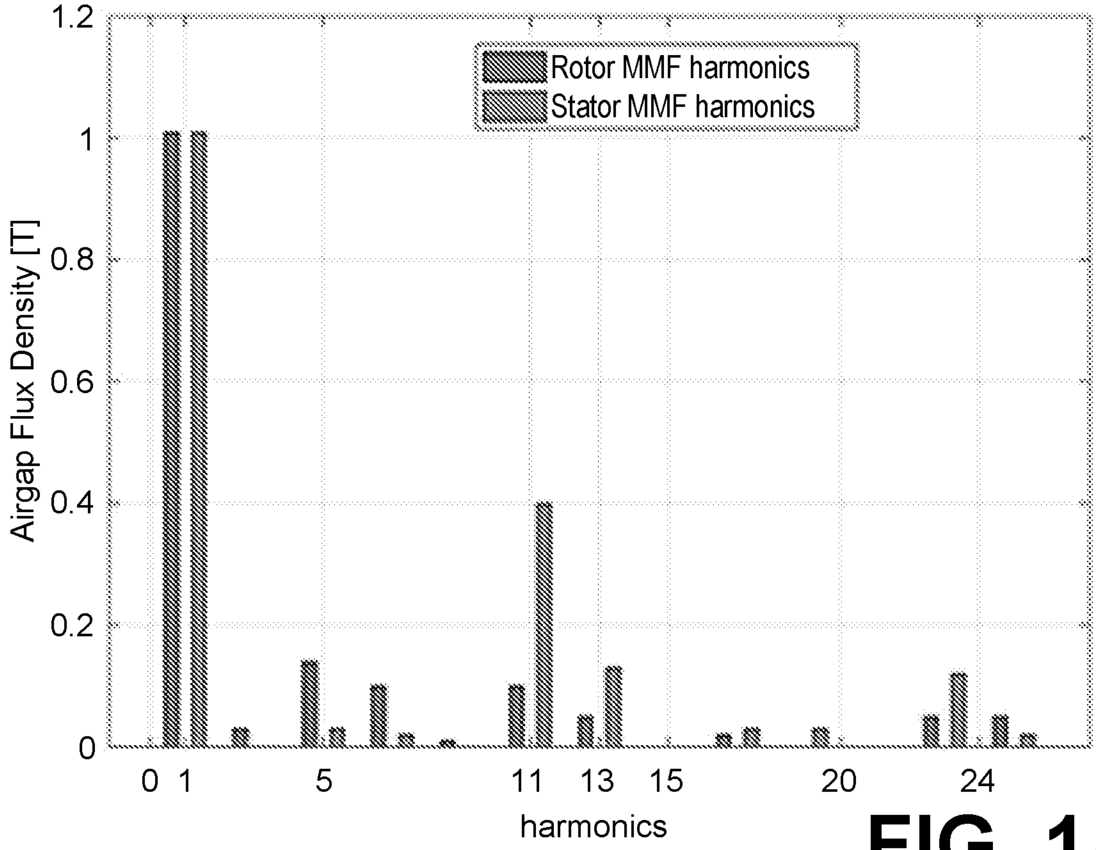

1.2
1
0.8
0.6
0.4
0.2
0
Airgap Flux Density [T]
Rotor MMF harmonics
Stator MMF harmonics
0 1 5 11 13 15 20 24
harmonics

FIG. 1A

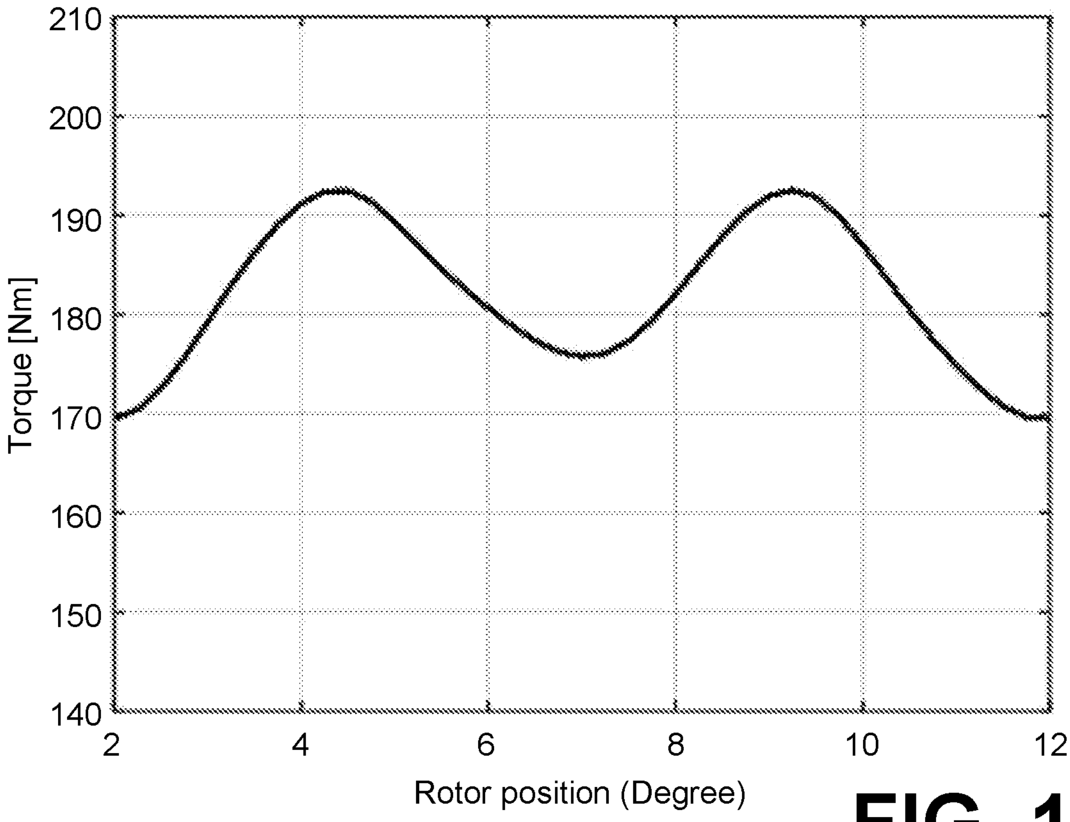

210
200
190
180
170
160
150
140
Torque [Nm]
2 4 6 8 10 12
Rotor position (Degree)

FIG. 1B

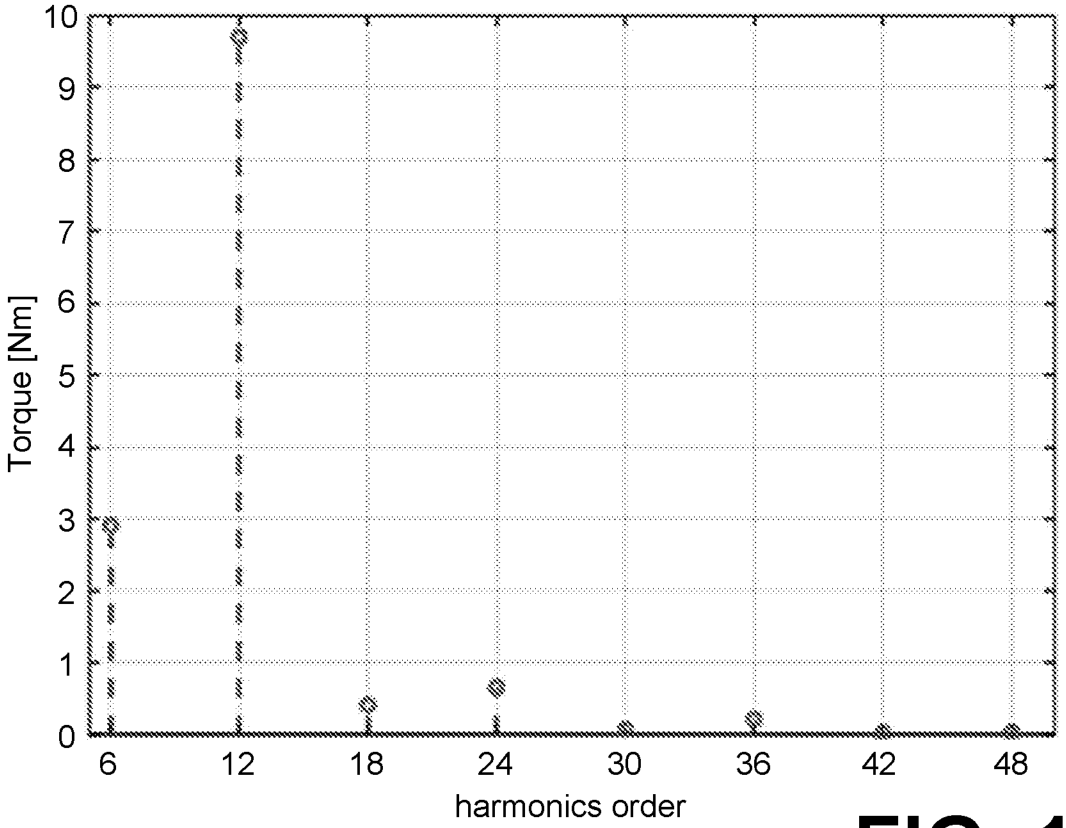


FIG. 1C

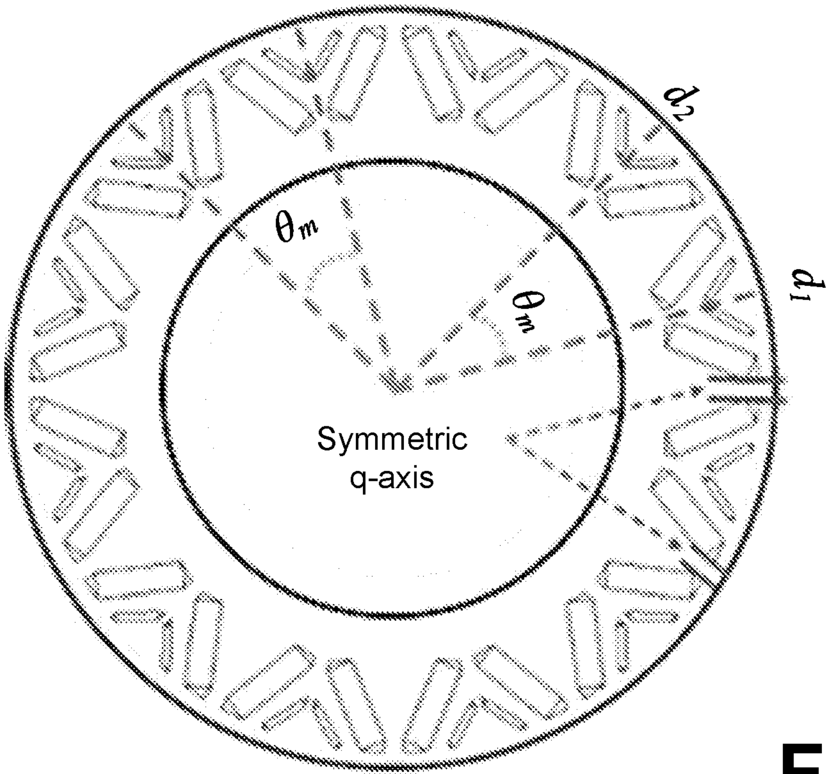

d_2
d_1
θ_m
θ_m
Symmetric
q-axis

FIG. 2A

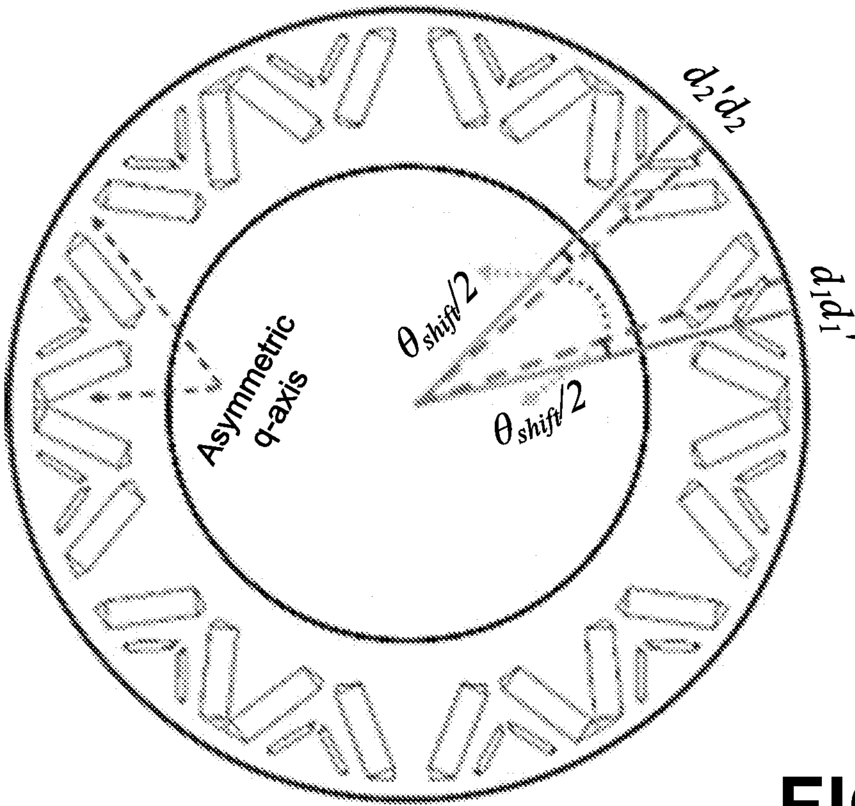

$d_2'd_2$
d_1d_1'
$\theta_{shift}/2$
$\theta_{shift}/2$
Asymmetric
q-axis

FIG. 2B

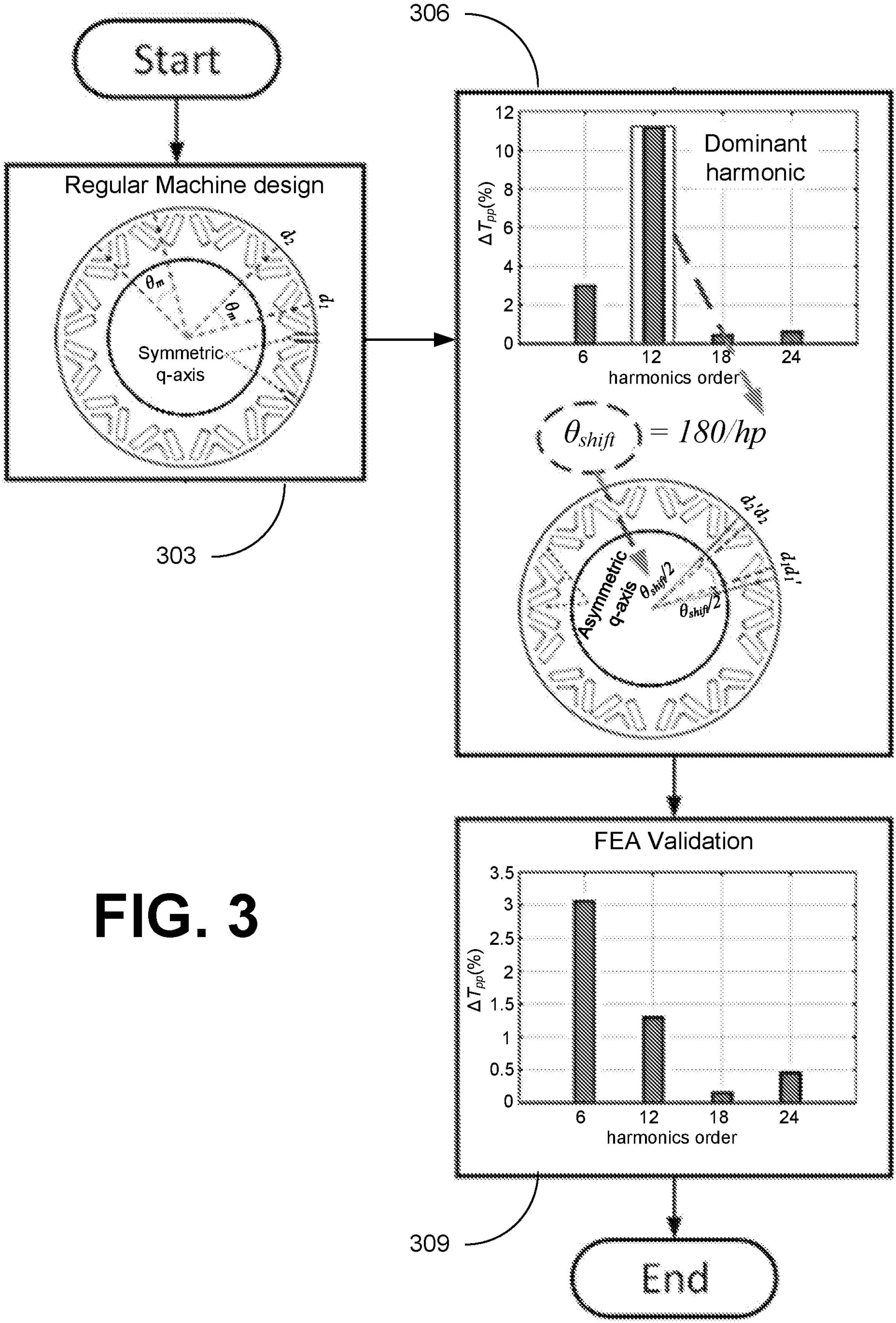

Start
Regular Machine design
Symmetric q-axis
303
306
Dominant harmonic
ΔT_pp(%)
harmonics order
θshift = 180/hp
Asymmetric q-axis
θshift/2
FEA Validation
309
End

FIG. 3

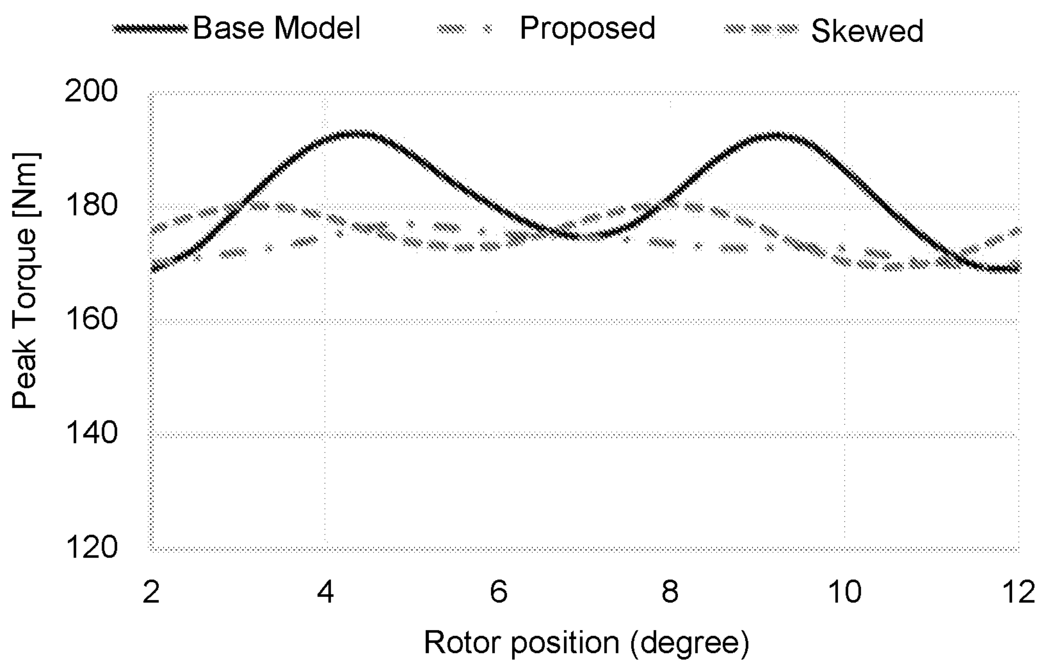

Base Model
Proposed
Skewed
200
180
160
140
120
Peak Torque [Nm]
2
4
6
8
10
12
Rotor position (degree)

FIG. 4A

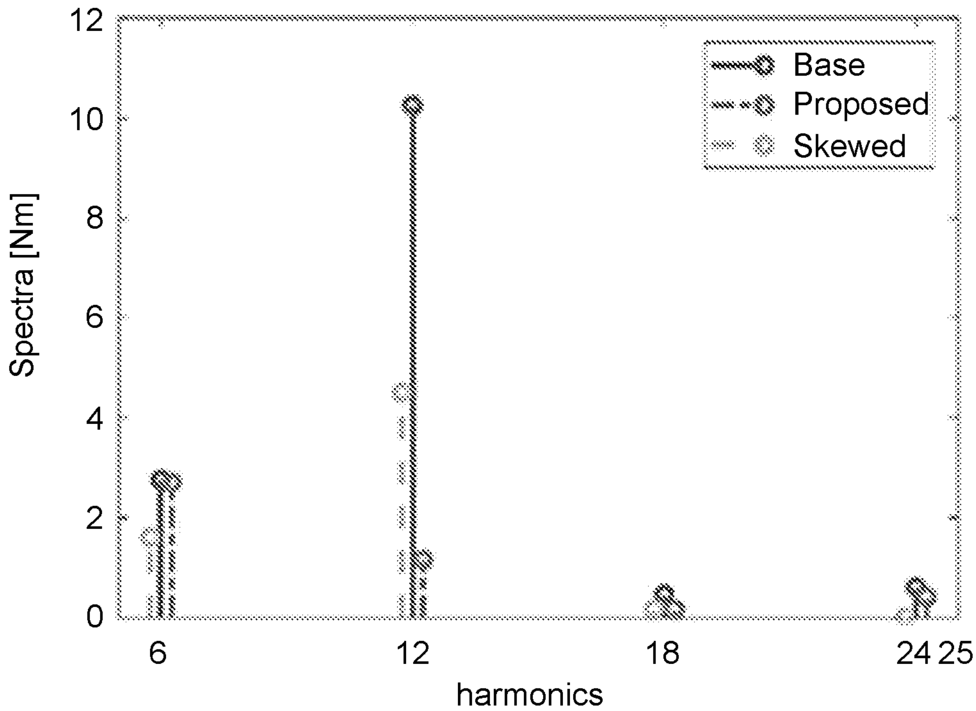

Base
Proposed
Skewed
12
10
8
6
4
2
0
Spectra [Nm]
6
12
18
24
25
harmonics

FIG. 4B

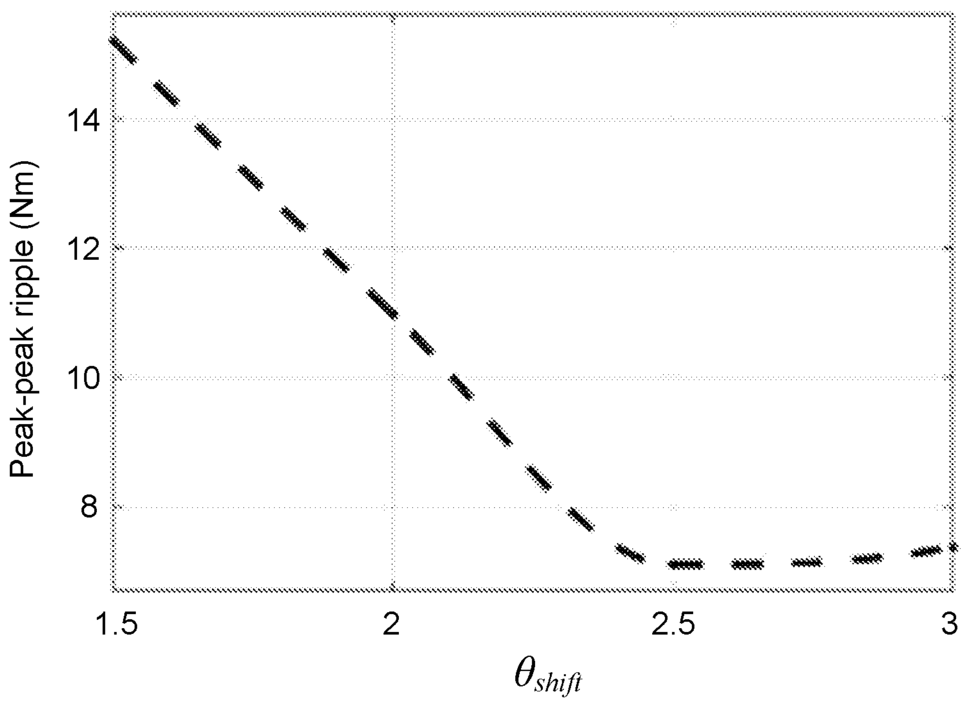

14
12
10
8
Peak-peak ripple (Nm)
1.5
2
2.5
3
θ_{shift}

FIG. 4C

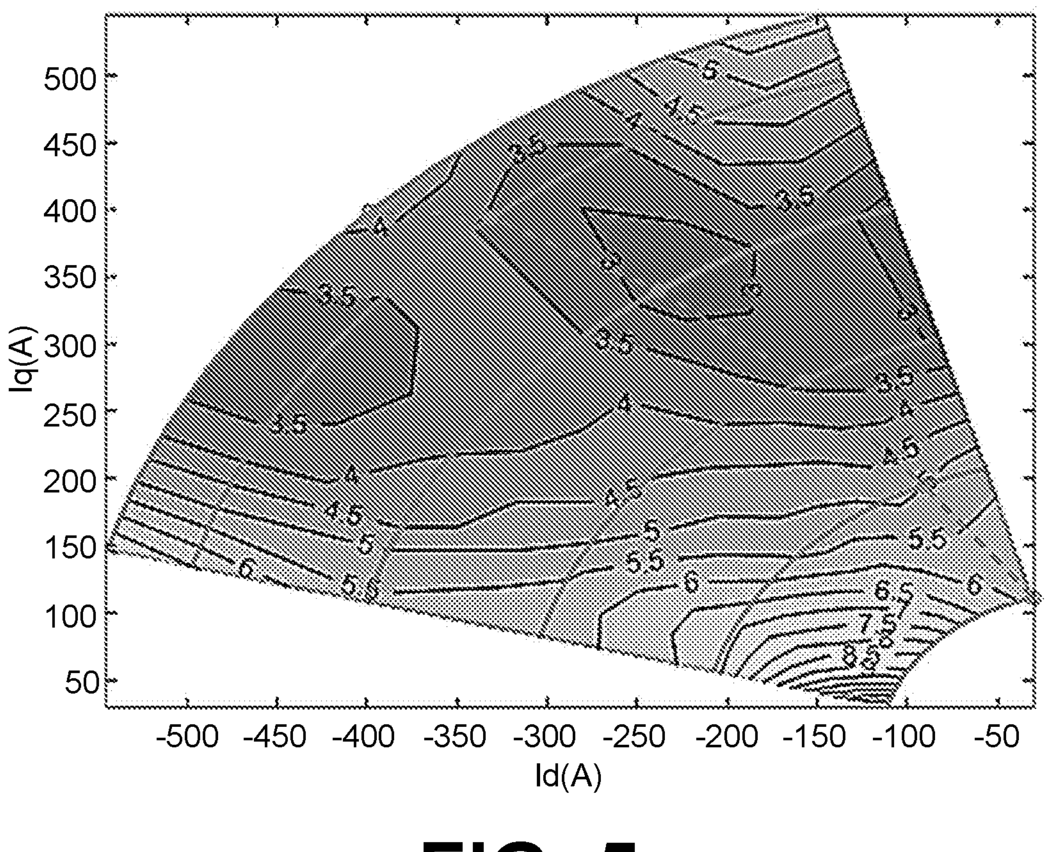

500
450
400
350
300
250
200
150
100
50
Iq(A)
-500
-450
-400
-350
-300
-250
-200
-150
-100
-50
Id(A)

FIG. 5

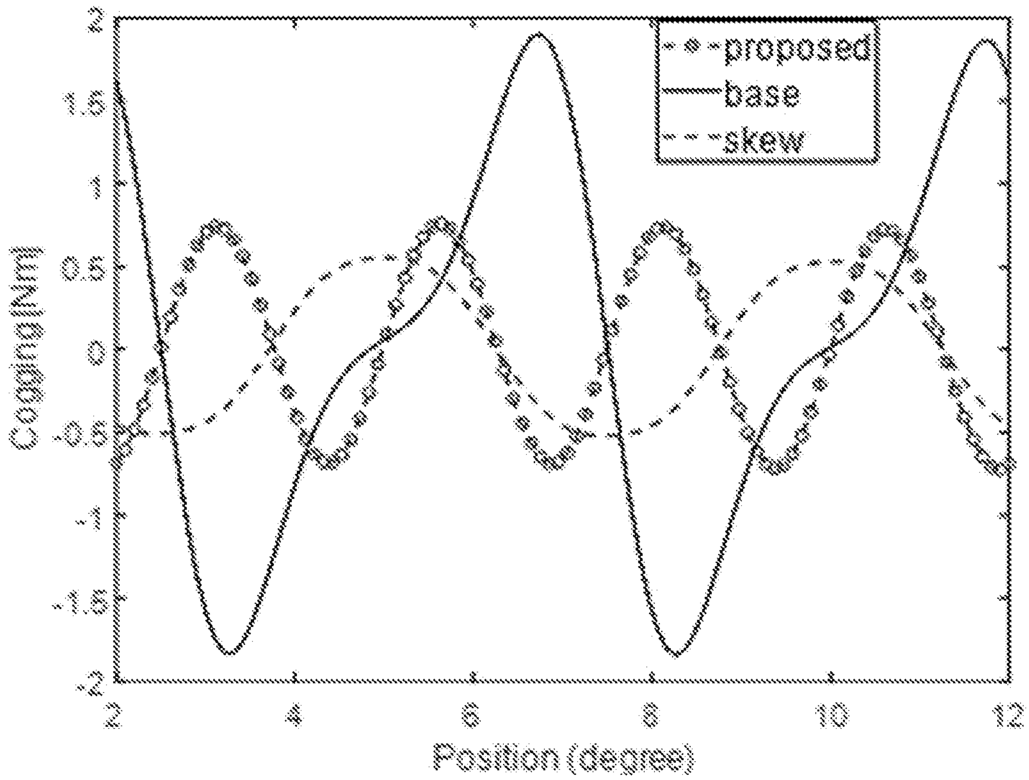

proposed
base
skew
Cogging[Nm]
Position (degree)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
2
4
6
8
10
12

FIG. 6

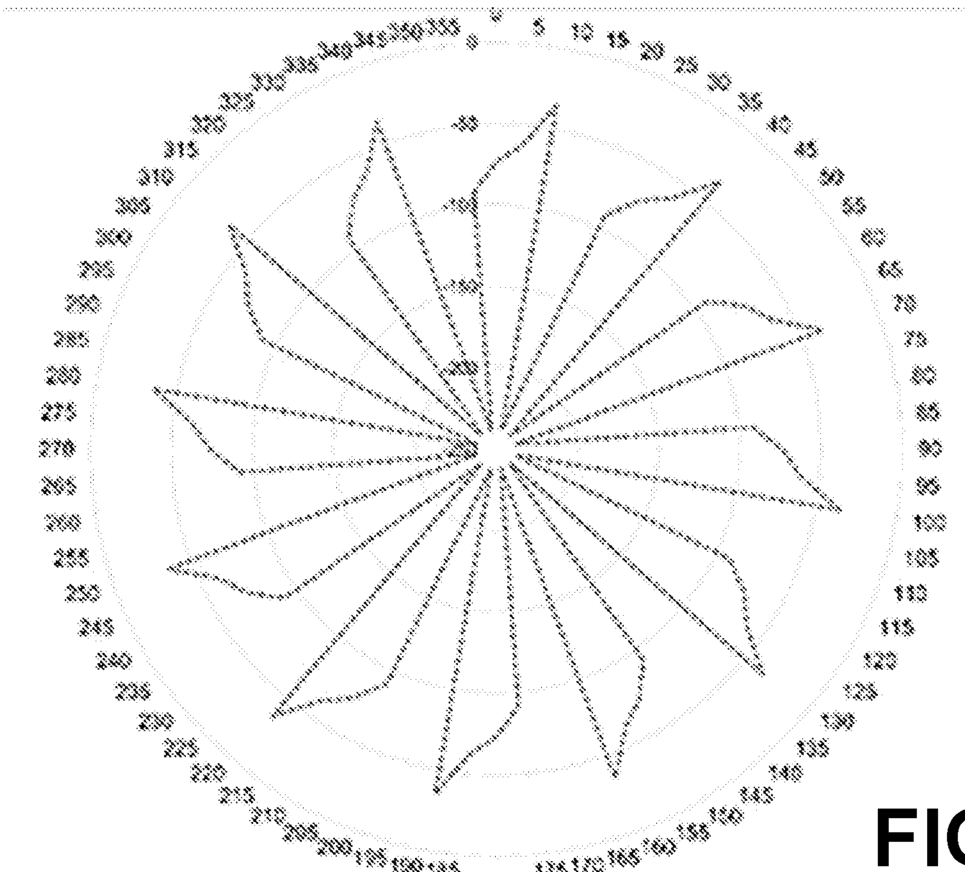


FIG. 7A

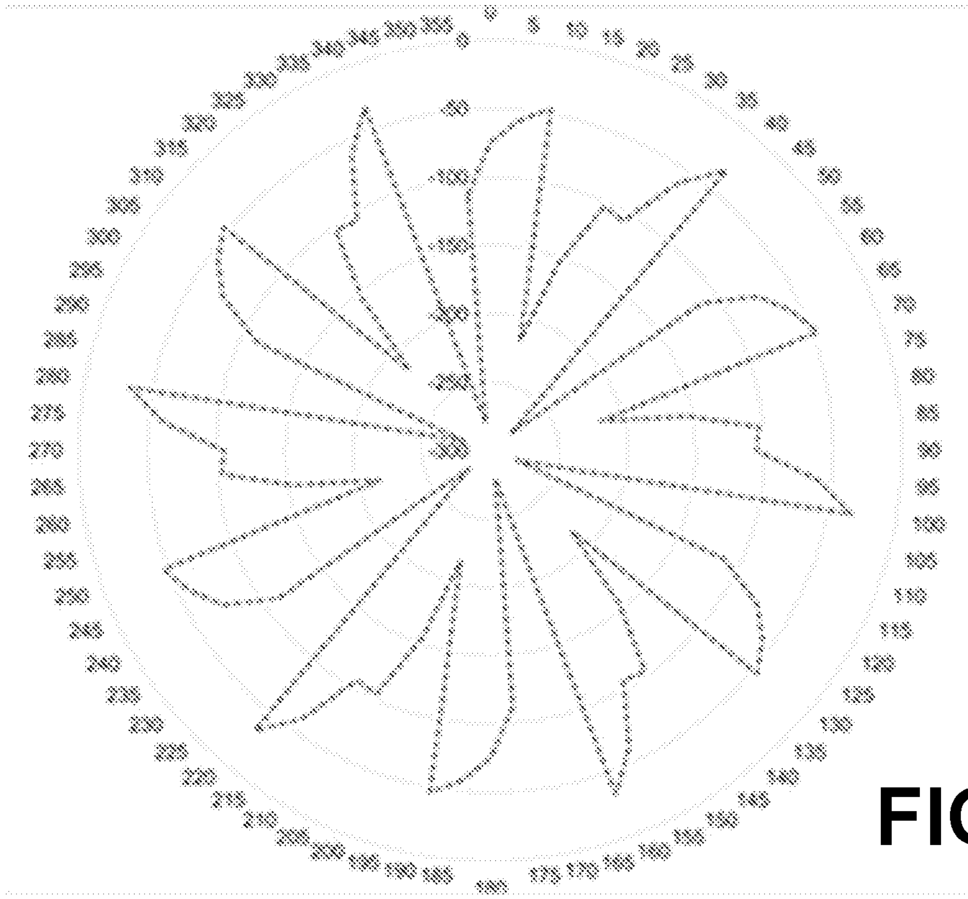


FIG. 7B

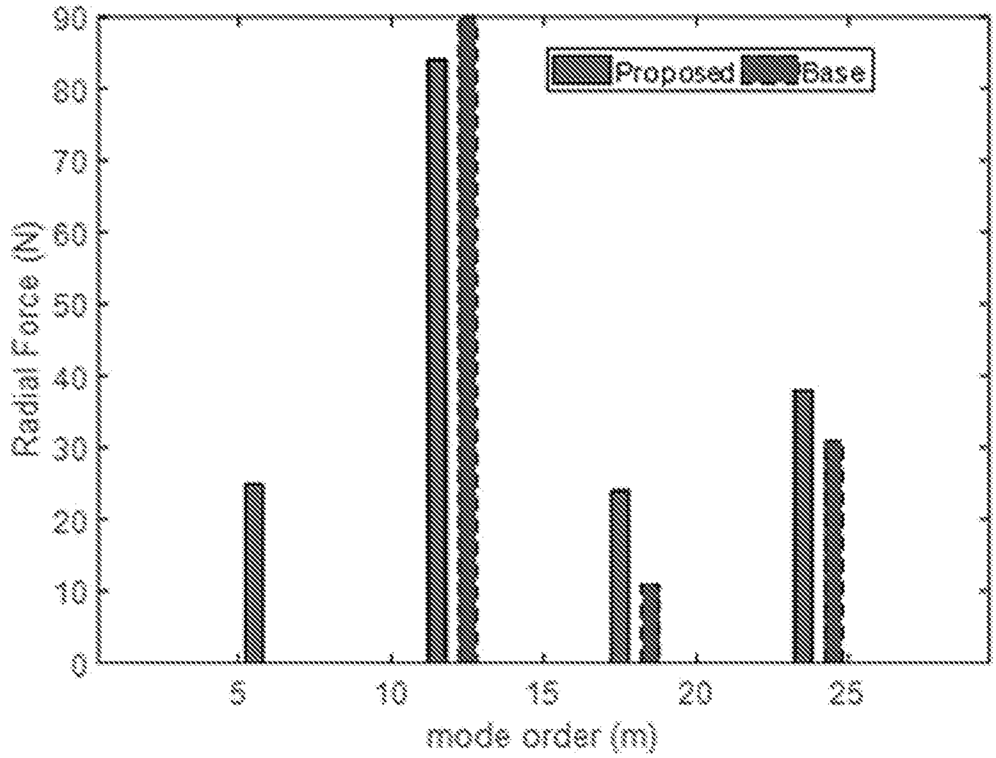

Proposed
Base
Radial Force (N)
mode order (m)
0
10
20
30
40
50
60
70
80
90
5
10
15
20
25

FIG. 7C

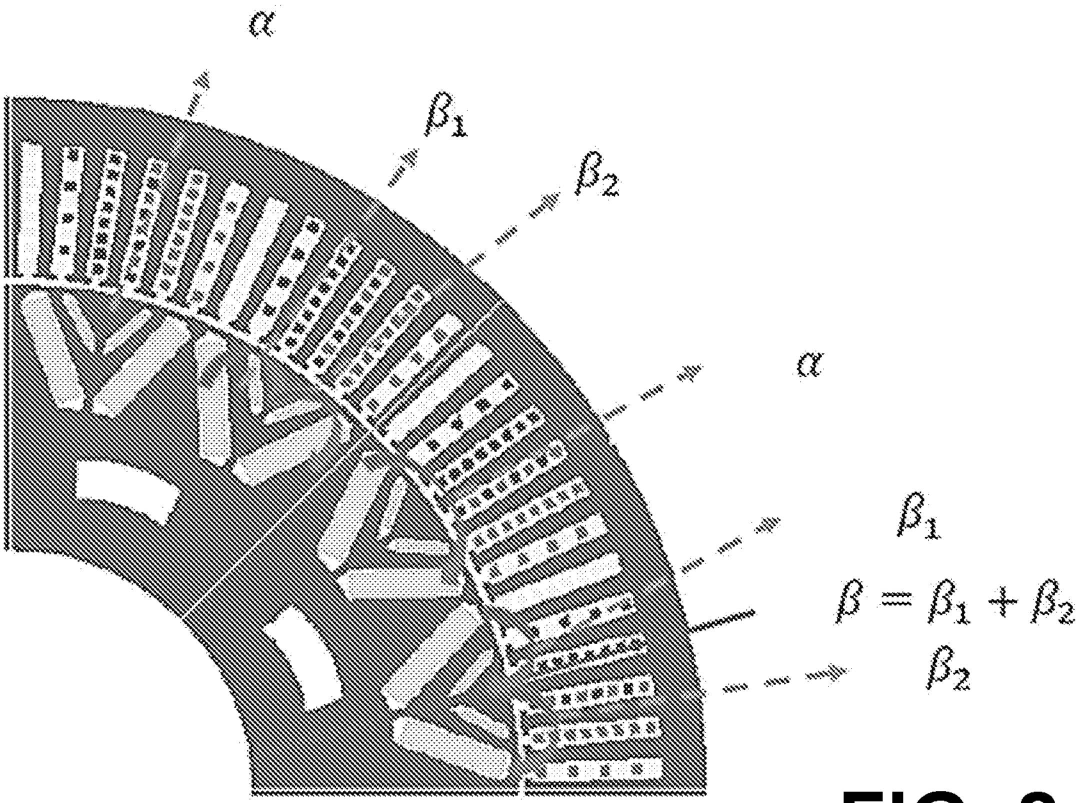

α
β_1
β_2
α
β_1
$\beta = \beta_1 + \beta_2$
β_2

FIG. 8

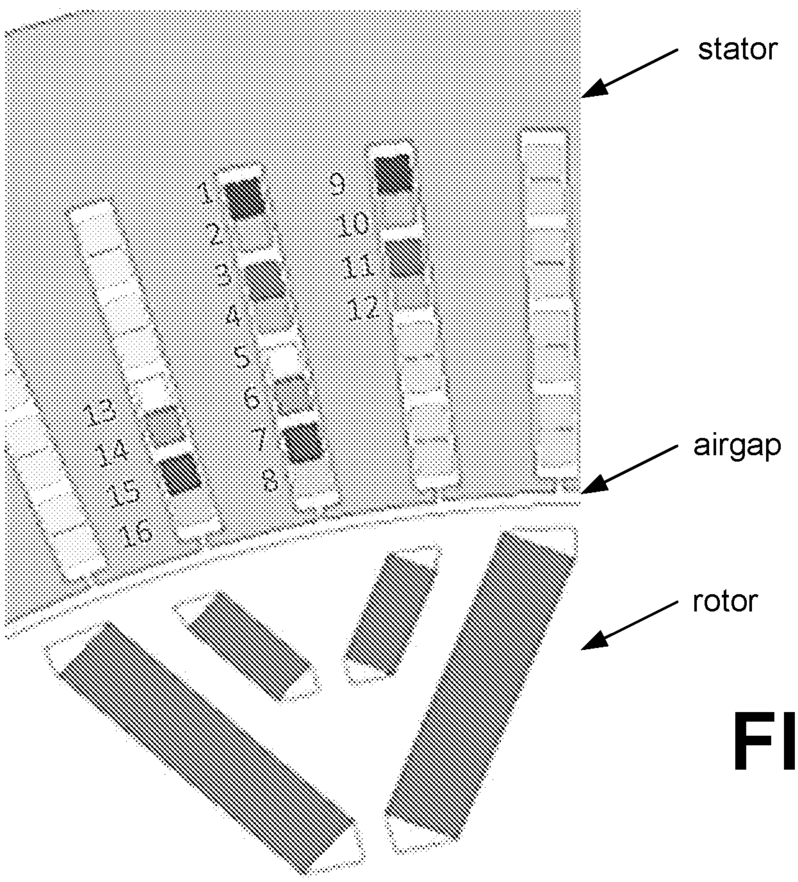

stator
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
airgap
rotor

FIG. 9A

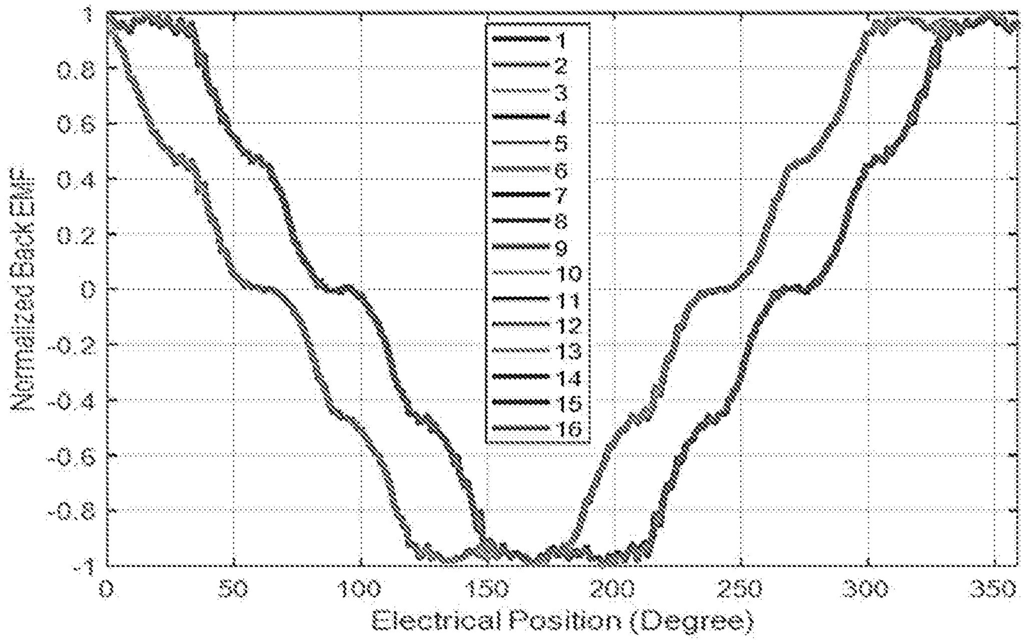


FIG. 9B

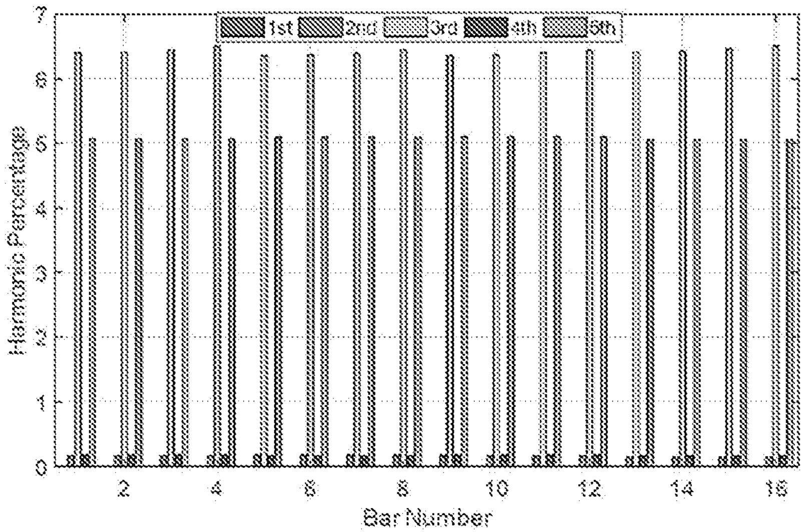


FIG. 9C

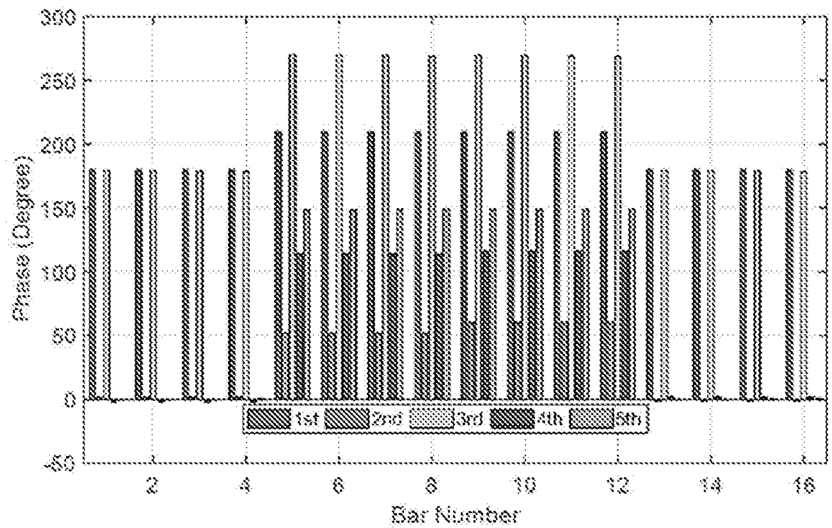


FIG. 9D

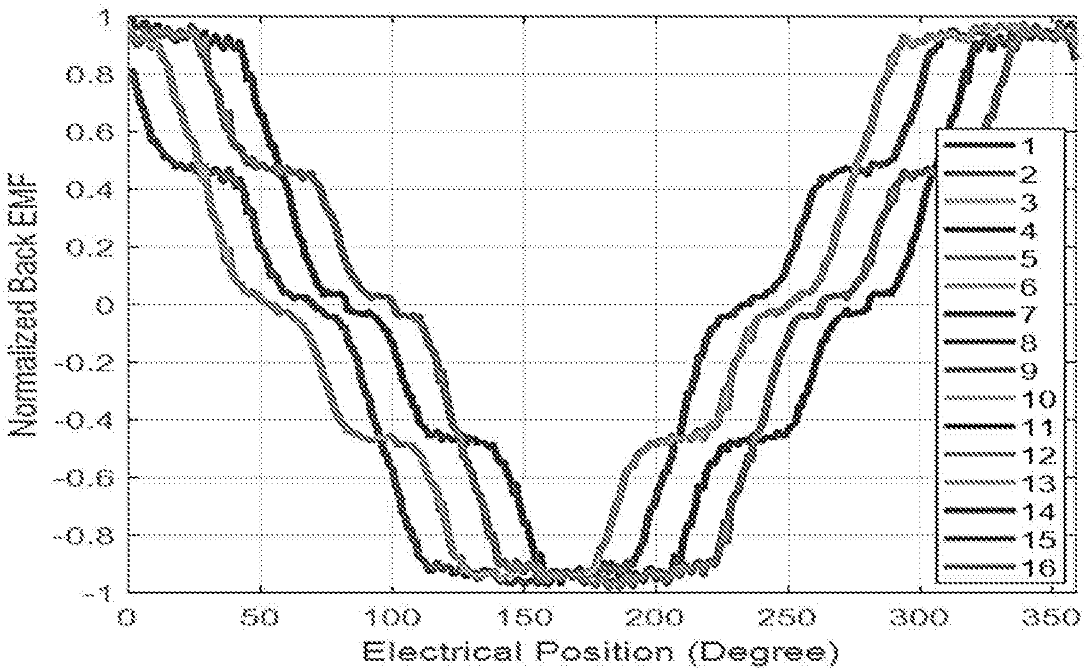


FIG. 10A

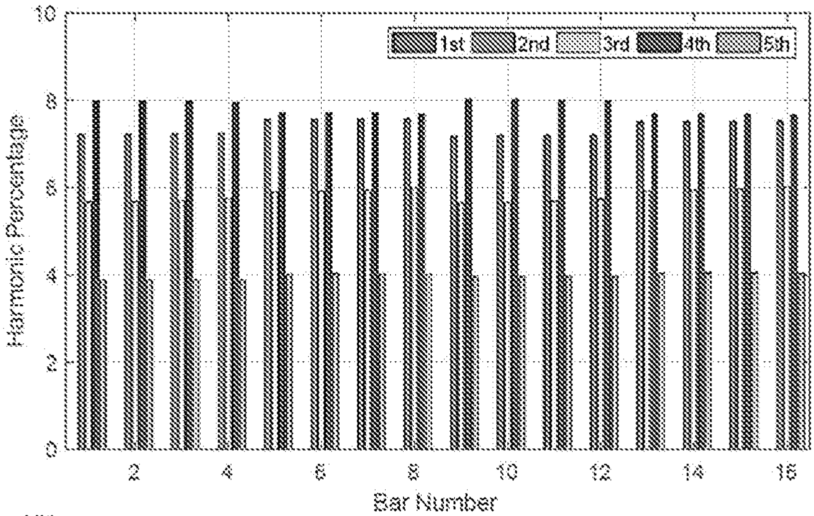


FIG. 10B

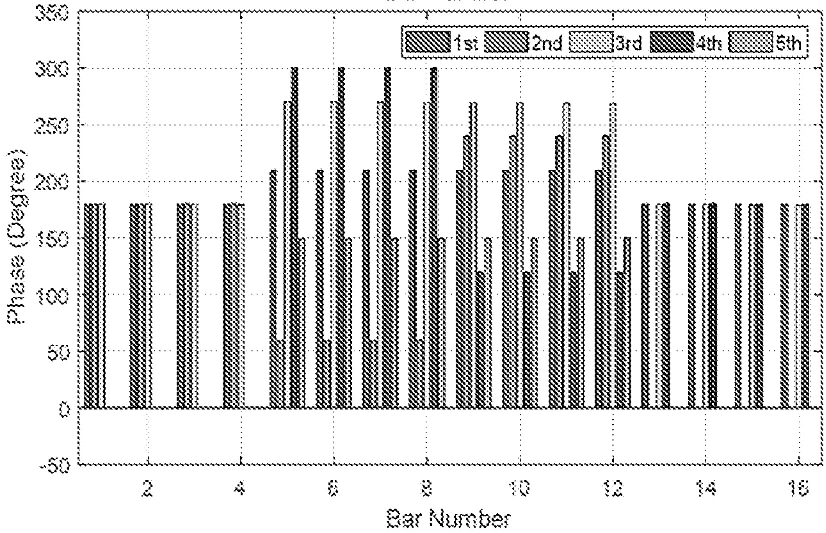


FIG. 10C

W1	01	09	08	16
W2	02	10	07	15
W3	03	11	06	14
W4	04	12	05	13

FIG. 11A

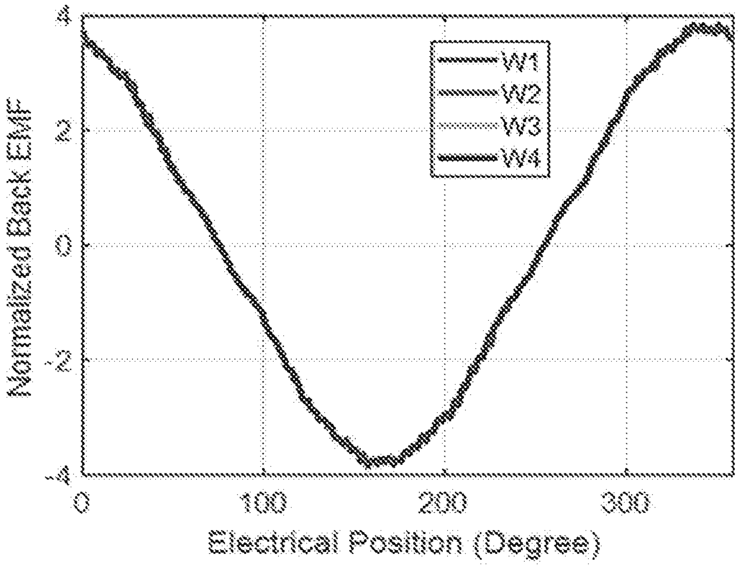


FIG. 11B

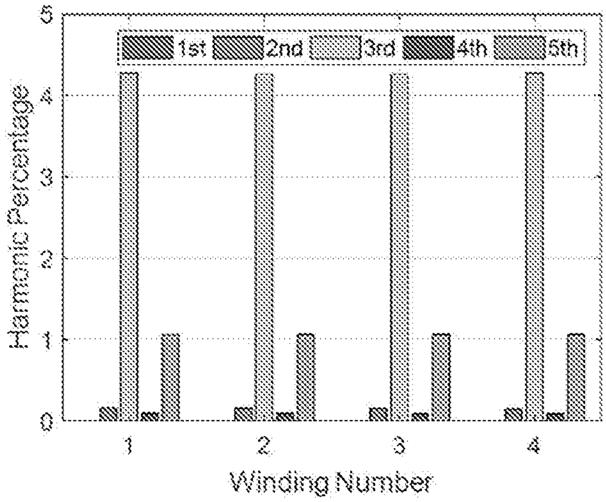


FIG. 11C

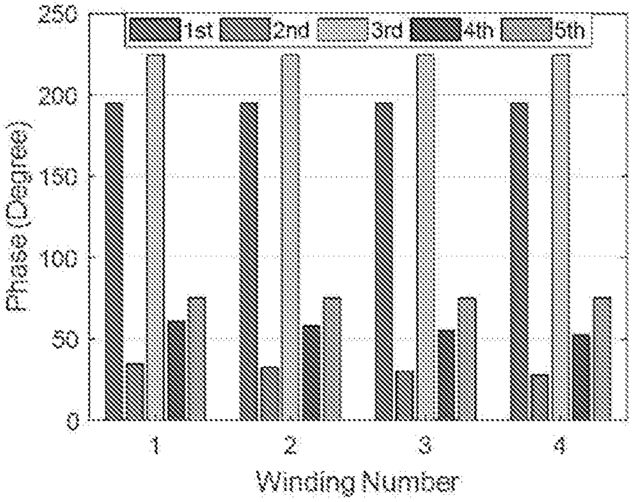


FIG. 11D

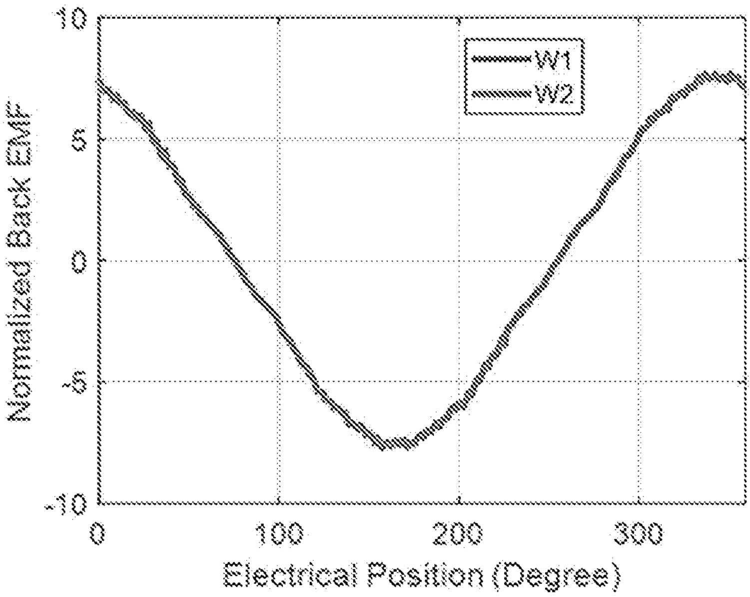


FIG. 11E

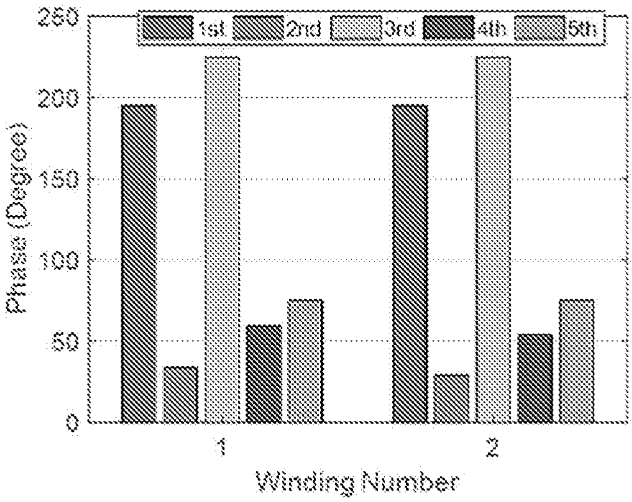


FIG. 11F

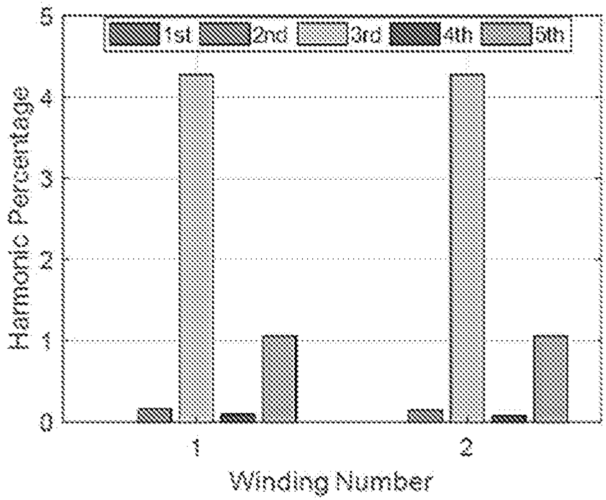


FIG. 11G

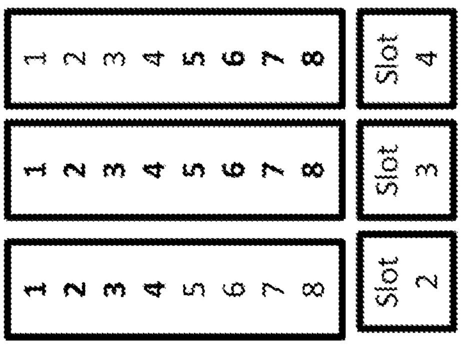


FIG. 12A

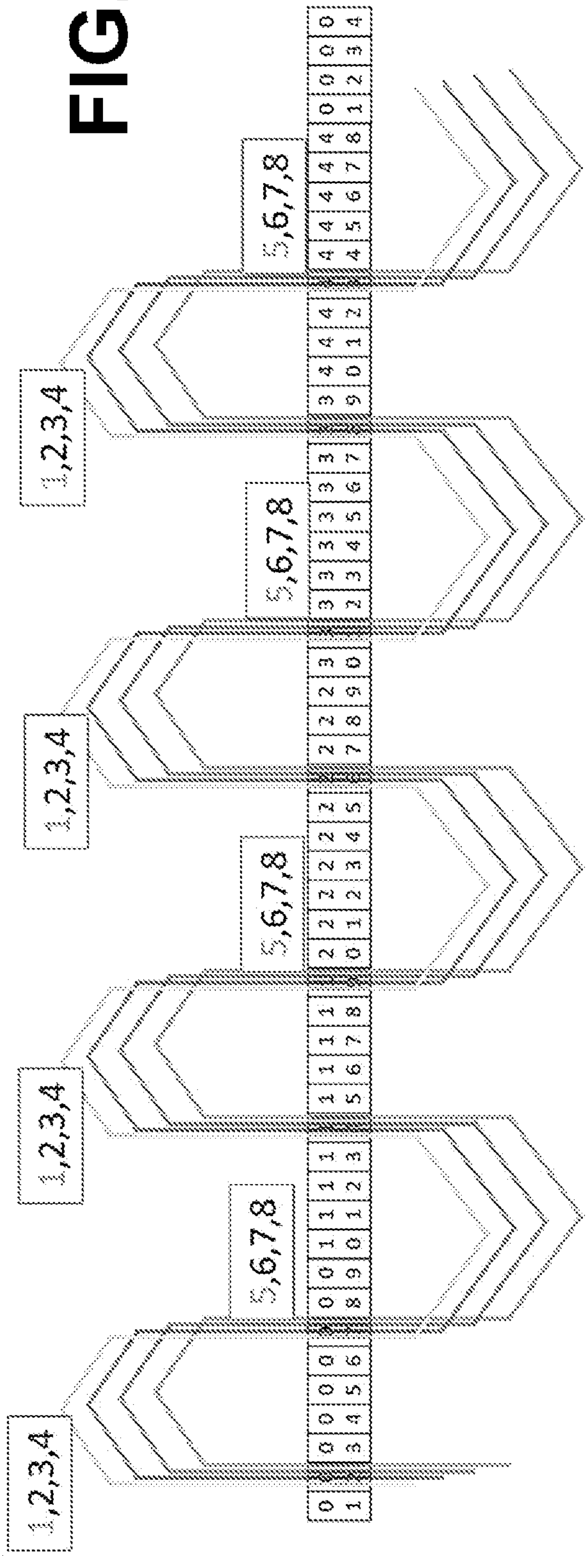


FIG. 12B

FIG. 12C

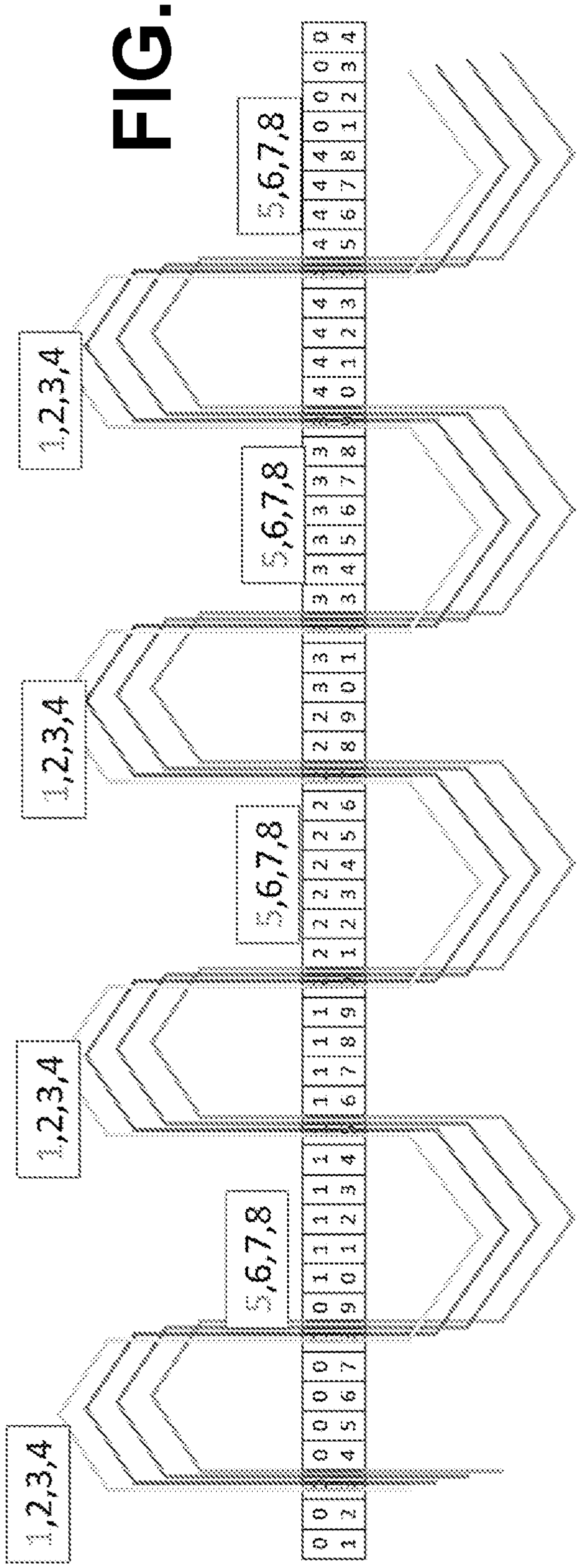


FIG. 12D

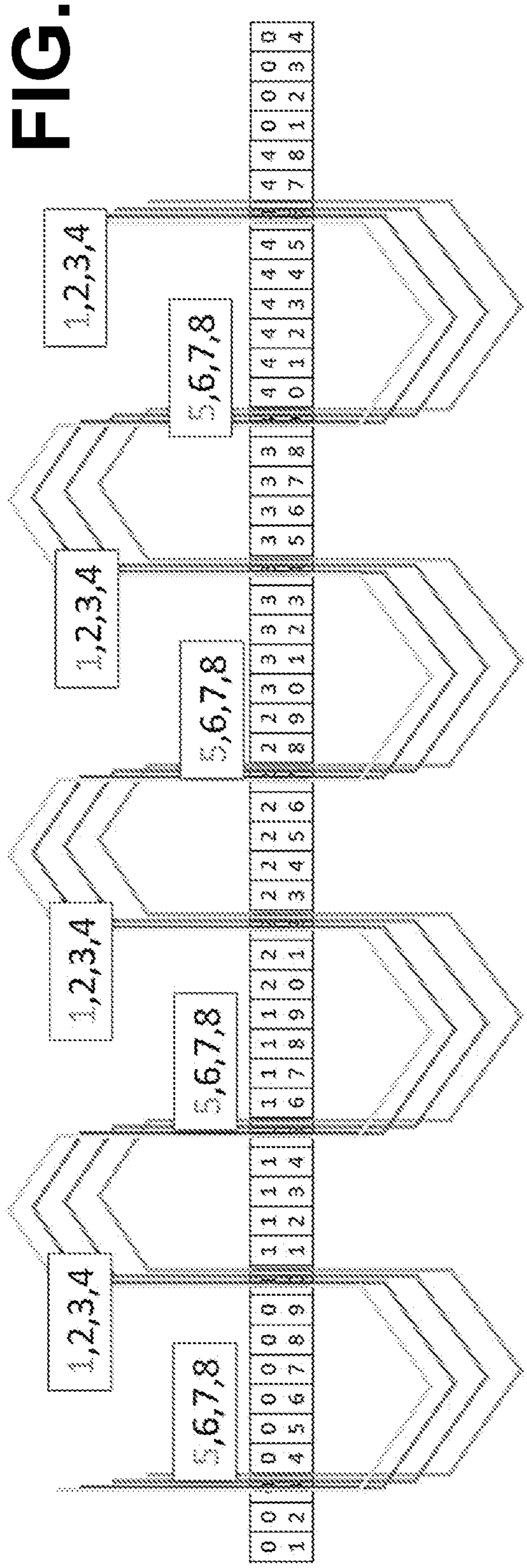
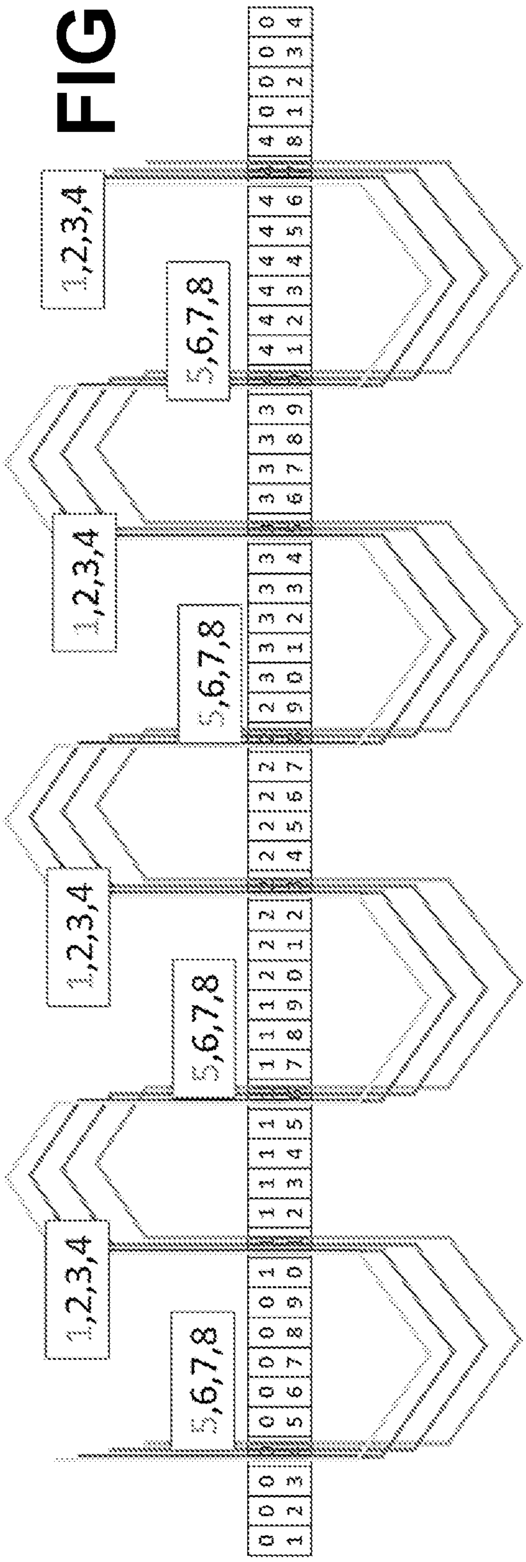


FIG. 12E



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US19/58962

A. CLASSIFICATION OF SUBJECT MATTER

IPC - H02K 1/06, 1/22, 1/24, 1/27, 29/03 (2019.01)

CPC - H02K 1/06, 1/22, 1/24, 1/27, 1/2706, 1/274, 1/2753, 1/276, 1/2766, 1/278, 29/03

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/0031843 A1 (LIANG, F et al.) 10 February 2011; abstract; figures 1A-1B & 8-9; paragraphs [0056 0069, & 0074-0076]	1-3
A	US 2018/0159392 A1 (ROCKWELL AUTOMATION TECHNOLOGIES, INC.) 07 June 2018; entire document	1-3
A	US 2016/0365762 A1 (FORD GLOBAL TECHNOLOGIES, LLC) 15 December 2016; entire document	1-3
A	US 2014/0103768 A1 (REGAL BELOIT AMERICA, INC.) 17 April 2014; entire document	1-3
A	US 2013/0069470 A1 (JURKOVIC, S et al.) 21 March 2013; entire document	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 December 2019 (30.12.2019)	18 MAR 2020

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Shane Thomas Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US19/58962

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-5 & 10-15
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Extra Sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-3

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

-***-Continued from Box No. III Observations where unity of invention is lacking-***-

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fee must be paid.

Group I: Claims 1-3 are directed towards a rotor having magnetic pole pairs separated by an angular displacement.
Group II: Claims 6-9 are directed towards a rotor having a plurality of magnetic poles including a magnetic arc.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical features of Group I include at least a plurality of magnetic pole pairs, where each of the magnetic pole pairs comprise a pair of poles separated by a first angular displacement (θ_1), and adjacent poles of adjacent magnetic pole pairs are separated by a second angular displacement (θ_2) greater than the first angular displacement by a shift angle (θ_shift = θ_2 – θ_1), which are not present in Group II.

The special technical features of Group II include at least where adjacent poles of the plurality of magnetic poles comprise a first pole having a first magnetic arc (α) and a second pole adjacent to the first magnetic pole, the second pole having a second magnetic arc (β), which are not present in Group I.

The common technical features shared by Groups I-II are a rotor assembly, a rotor core; and a plurality of magnetic poles distributed about the rotor core adjacent to an outer surface of the rotor core.

However, these common features are previously disclosed by US 2014/0103768 A1 to Regal Beloit America, Inc. (hereinafter "Regal"). Regal discloses a rotor assembly (electric motor 10 includes rotatable assembly 20 (rotor assembly); figures 1-4; paragraph [0031]), a rotor core (rotatable assembly 20 includes permanent magnet rotor core 36; figures 1-4; paragraph [0032]); and a plurality of magnetic poles distributed about the rotor core adjacent to an outer surface of the rotor core (rotor core 36 includes a plurality of rotor poles 58 each having an outer wall 60 along a rotor outer edge 40; figures 1-4; paragraph [0037]).

Since the common technical features are previously disclosed by the Regal reference, these common features are not special and so Groups I-II lack unity.