



(51) International Patent Classification:

H02K 1/24 (2006.01) *H02K 29/00* (2006.01)
H02K 1/16 (2006.01) *B25F 5/00* (2006.01)
H02K 1/27 (2006.01) *H02K 7/14* (2006.01)
H02K 3/12 (2006.01)

(21) International Application Number:

PCT/US2020/056568

(22) International Filing Date:

21 October 2020 (21.10.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/924,329 22 October 2019 (22.10.2019) US

(71) Applicant: **MILWAUKEE ELECTRIC TOOL CORPORATION** [US/US]; 13135 West Lisbon Road, Brookfield, WI 53005 (US).

(72) Inventor: **BOULANGER, Keith**; 6321 73rd Street, Apt. 102, Kenosha, WI 53142 (US).

(74) Agent: **RIEDL, Jared, D.**; Michael Best & Friedrich LLP, 790 N. Water Street, Ste. 2500, Wilwaukee, WI 53202 (US).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,

(54) Title: POWER TOOL WITH PERMANENT MAGNET SYNCHRONOUS RELUCTANCE MACHINE

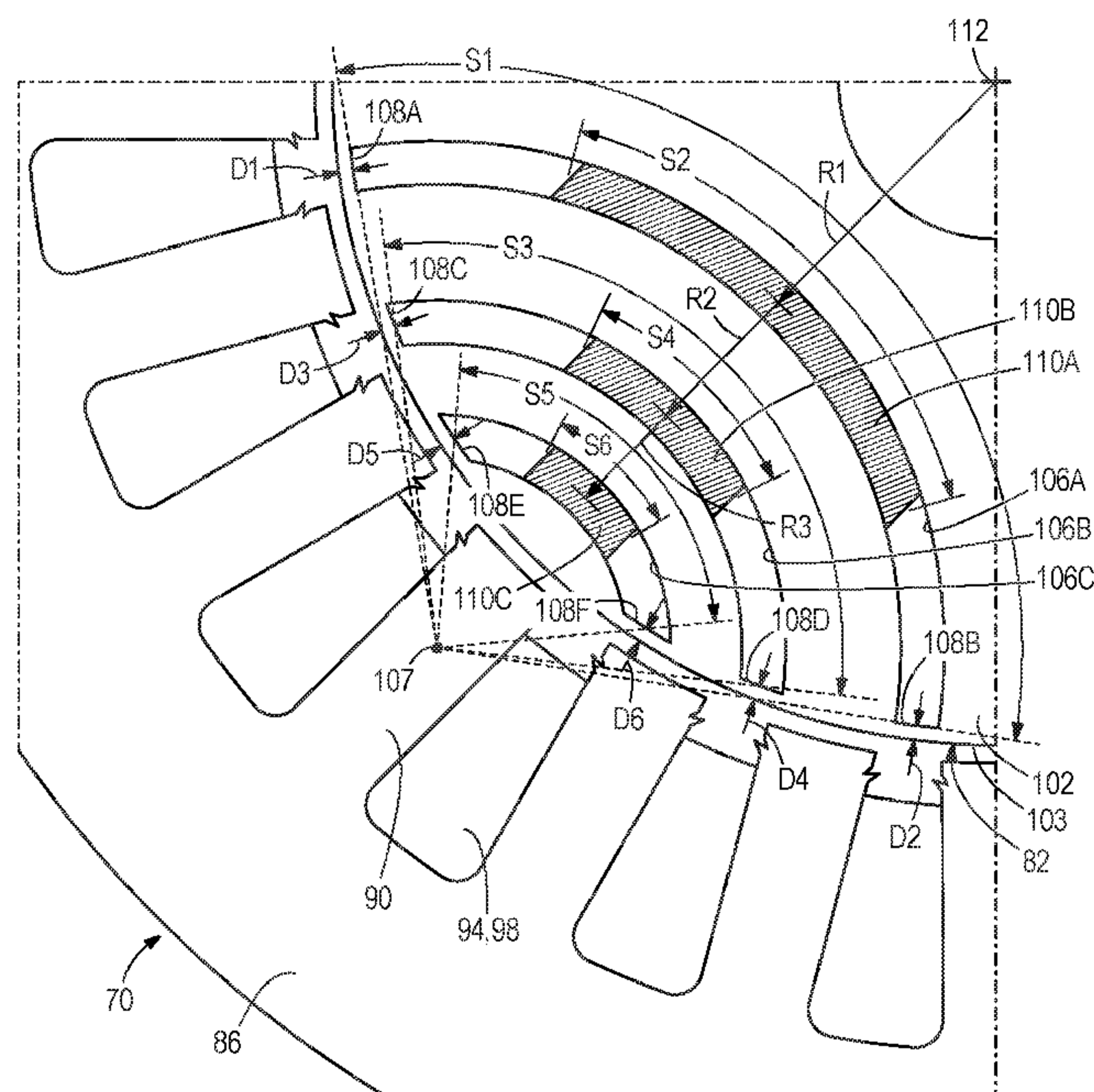


FIG. 6

(57) Abstract: A power tool including a housing and a motor assembly positioned within the housing. The motor assembly includes a stator with winding slots that receive stator windings and a rotor. The rotor includes a rotor body with a first slot positioned a first distance from a center of the rotor body, a second slot positioned a second distance from the center of the rotor body, and a third slot positioned a third distance from the center of the rotor body. The first slot, the second slot, and the third slot are curved about a common center. The rotor further includes a first magnet positioned within the first slot, a second magnet positioned within the second slot, and a third magnet positioned within the third slot.



UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

**POWER TOOL WITH PERMANENT MAGNET
SYNCHRONOUS RELUCTANCE MACHINE**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/924,329, filed on October 22, 2019, the entire content of which is incorporated herein by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates to power tools, and more particularly to power tools with a permanent magnet motors.

SUMMARY OF THE DISCLOSURE

[0003] The disclosure provides a power tool including a housing and a motor assembly positioned within the housing. The motor assembly includes a stator with winding slots that receive stator windings and a rotor. The rotor includes a rotor body with a first slot positioned a first distance from a center of the rotor body and a second slot positioned a second distance from the center of the rotor body. The first slot and the second slot are curved about a common center. The rotor further includes a first magnet positioned within the first slot and a second magnet positioned within the second slot.

[0004] The disclosure provides a motor assembly for a power tool that includes a stator with winding slots that receive stator windings, and a rotor including a rotor body with a first slot positioned a first distance from a center of the rotor body and a second slot positioned a second distance from the center of the rotor body. The first slot and the second slot are each curved about a common point. The rotor further includes a first magnet positioned within the first slot and a second magnet positioned within the second slot.

[0005] In some aspects, the common point is positioned outside of the rotor body.

[0006] In some aspects, a first dimension is measured between a first end of the first slot and an outer circumferential surface of the rotor body, a second dimension is measured between a second end of the first slot and the outer circumferential surface of the rotor body, and the second dimension is equal to the first dimension.

[0007] In some aspects, a first dimension is measured between an end of the first slot and an outer circumferential surface of the rotor body, a second dimension is measured between an end of the second slot and the outer circumferential surface of the rotor body, and the second dimension is equal to the first dimension.

[0008] In some aspects, the first magnet spans within a range of 50% to 100% of the first slot.

[0009] In some aspects, the first magnet spans within a range of 50% to 56% of the first slot.

[0010] In some aspects, the first magnet spans 53% of the first slot.

[0011] In some aspects, the second magnet spans within a range of 33% to 100% of the second slot

[0012] In some aspects, the second magnet spans within a range of 33% to 39% of the second slot.

[0013] In some aspects, the second magnet spans 36% of the second slot.

[0014] In some aspects, a third slot is positioned a third distance from the center of the rotor body, the third slot is curved about the common point, and a third magnet positioned within the third slot.

[0015] In some aspects, the third magnet spans within a range of 35% to 100% of the third slot.

[0016] In some aspects, the third magnet spans within a range of 35% to 41% of the third slot.

[0017] In some aspects, the third magnet spans 38% of the third slot.

[0018] In some aspects, the motor is configured to drive a cyclical load.

[0019] In some aspects, the motor provides more startup torque than a brushless DC motor with a same package size and provides a higher no-load speed than the brushless DC motor with the same package size.

- [0020] In some aspects, a tool element and wherein the tool element is driven by the motor.
- [0021] In some aspects, the stator includes at least twenty-four slots.
- [0022] In some aspects, the rotor is a 4-pole rotor.
- [0023] The disclosure provides a power tool including a housing and a permanent magnet synchronous reluctance machine positioned within the housing. The permanent magnet synchronous reluctance machine includes a stator with stator windings, a rotor with a plurality of slots, and a magnet positioned within each of the plurality of slots. The power tool further includes a tool element driven by the permanent magnet synchronous reluctance machine.
- [0024] In some aspects, the permanent magnet synchronous reluctance machine provides more startup torque than a brushless DC motor with a same package size and provides higher no-load speed than the brushless DC motor with the same package size.
- [0025] In some aspects, the plurality of slots are curved.
- [0026] In some aspects, the magnet within each of the plurality of slots span less than 56% of the slot.
- [0027] In some aspects, the permanent magnet synchronous reluctance machine includes at least twenty-four winding slots formed in the stator and the rotor includes at least four poles.
- [0028] Before any embodiments are explained in detail, it is to be understood that the embodiments are not limited in its application to the details of the configuration and arrangement of components set forth in the following description or illustrated in the accompanying drawings. The embodiments are capable of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein are for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having” and variations thereof are meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms “mounted,” “connected,” “supported,” and “coupled” and

variations thereof are used broadly and encompass both direct and indirect mountings, connections, supports, and couplings.

[0029] In addition, it should be understood that embodiments may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic-based aspects may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processing units, such as a microprocessor and/or application specific integrated circuits (“ASICs”). As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components, may be utilized to implement the embodiments. For example, “servers,” “computing devices,” “controllers,” “processors,” etc., described in the specification can include one or more processing units, one or more computer-readable medium modules, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

[0030] Relative terminology, such as, for example, “about,” “approximately,” “substantially,” etc., used in connection with a quantity or condition would be understood by those of ordinary skill to be inclusive of the stated value and has the meaning dictated by the context (e.g., the term includes at least the degree of error associated with the measurement accuracy, tolerances [e.g., manufacturing, assembly, use, etc.] associated with the particular value, etc.). Such terminology should also be considered as disclosing the range defined by the absolute values of the two endpoints. For example, the expression “from about 2 to about 4” also discloses the range “from 2 to 4”. The relative terminology may refer to plus or minus a percentage (e.g., 1%, 5%, 10%, or more) of an indicated value.

[0031] It should be understood that although certain drawings illustrate hardware and software located within particular devices, these depictions are for illustrative purposes only. Functionality described herein as being performed by one component may be performed by multiple components in a distributed manner. Likewise, functionality performed by multiple components may be consolidated and performed by a single component. In some embodiments, the illustrated components may be combined or divided into separate software, firmware and/or hardware. For example, instead of being located

within and performed by a single electronic processor, logic and processing may be distributed among multiple electronic processors. Regardless of how they are combined or divided, hardware and software components may be located on the same computing device or may be distributed among different computing devices connected by one or more networks or other suitable communication links. Similarly, a component described as performing particular functionality may also perform additional functionality not described herein. For example, a device or structure that is “configured” in a certain way is configured in at least that way but may also be configured in ways that are not explicitly listed.

[0032] Other aspects of the disclosure will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] FIG. 1 illustrates various power tool applications with cyclical loads that require a high startup torque and high no-load speed.

[0034] FIG. 2 is a graph of an example of a cyclical load of the power tool applications of FIG 1, illustrated as torque as a function angular position.

[0035] FIG. 3 is a graph illustrating electrical characteristic for a conventional motor as a function of torque, with various operating points associated with the power tool loading identified.

[0036] FIG. 4 is a graph illustrating the torque capability of a power tool motor as a function of angular position, with a minimum torque requirement level identified.

[0037] FIG. 5 is a cross-sectional view of a permanent magnet synchronous reluctance machine (“PMSRM”), according to embodiments described herein.

[0038] FIG. 6 is an enlarged partial view of the PMSRM of FIG. 5.

[0039] FIG. 6A is an enlarged partial view of a PMSRM, according to another embodiment described herein.

[0040] FIG. 7 is a graph comparing speed, output power, and efficiency of a conventional interior permanent magnet (“IPM”) motor with the permanent magnet synchronous reluctance machine of FIG. 5.

DETAILED DESCRIPTION

[0041] Power tools that include an electric motor for driving fans, pumps, compressors, etc., experience variable load conditions. For example, one load condition may be a high startup torque requirement, while a second load condition may be a high no-load speed. Furthermore, the load conditions may be cyclical. As such, the electric motor must be appropriately sized to meet a variety of load requirements of the power tool.

[0042] With reference to FIG. 1, various power tools (e.g., cable cutter 10, cable cutter 14, and air pump 18) are illustrated. In alternative embodiments, the power tool may be an electrical crimper, a knockout tool, a pump (hydraulic, air, or water), a spreading tool, a press tool, or any other similar power tool. The power tools 10, 14, 18 operate in applications with a large startup torque requirement and a cyclical load (i.e., a repeating load profile) once the power tool motor has reached normal operating speed. The power tools 10, 14, 18 each include a housing 12, 16, 20 a driven tool element (i.e., a working element). For example, the tool element may be a claw 21, a jaw, a cutter 22, a bit, a piston, a crimper, a punch, etc. depending on the power tool application.

[0043] With reference to FIG. 2, a first pump torque profile 24 and a second pump torque profile 26 are shown in inch-lbs. as a function of the rotational position (e.g., degrees) for a given maximum working pressure. When a pump in a power tool application is utilized, the pump piston reciprocates, slowly increasing pressure. During normal operation, the motor requires little power because of the rotationally stored energy of the motor, and the cyclical nature of the loading. In other words, normal operation of the pump is a high-speed and low torque scenario. In contrast, when the pump is stopped and a maximum pressure is acting on the piston, a substantial amount of torque is required (i.e., a high startup torque). The pump piston can stop during use just before its peak torque shown in FIG. 2, such that when the tool is turned back on there is a need for a very large startup torque. As such, the power tools 10, 14, 18 must include a motor that is sized to accommodate various worst-case loading scenarios, which can lead to costly and oversized motors.

[0044] With reference to FIG. 3, the pump loading scenario for a conventional power tool having a brushless DC (“BLDC”) motor, for example an interior permanent magnet (“IPM”) motor, is illustrated. In other words, the electrical characteristics of a conventional IPM motor in a pump application are illustrated in FIG. 3. Specifically, FIG. 3 illustrates the

efficiency 30, the output power 34, the current 38, and the speed 42 of the IPM motor as a function of torque. Various torque levels corresponding to various pump operating points are shown as vertical lines in FIG. 3. In particular, a low-torque, high speed no-load condition 46 during pressure build and ram extension, an average load condition 50, a peak load condition 54, and a stall load condition 58 (e.g., for pressure dump at maximum pressure, or startup torque) indicated as outside the capabilities of the conventional motor. The motor spends much of its operation either in the no-load condition 46 or the start-up for heavy loads 58.

[0045] With reference to FIG. 4, the motor stall torque (in inch ounce-force) as a function of rotational position is illustrated. In particular, a motor torque 62 for a first operating voltage (e.g., 19.5 Volts) and a motor torque 66 for a second operating voltage (e.g., 17.5 Volts) as a function of rotational position (degrees). As discussed above, in some situations the pump piston can stop at a high compression stroke, and the motor can be in a rotational position that does not produce sufficient torque experience to be able to startup. In other words, the horizontal line 70 indicates the minimum torque requirements to achieve proper startup at a maximum pressure. In the illustrated embodiment, the horizontal line 70 is 76 oz-in and is representative of the peak load as maximum pressure. If the motor torque 62, 66 falls below the horizontal line 70 it creates a possible stall point 72 (FIG. 4) and the power tool may not properly start. As a result, power tool designs include larger and more powerful motors than what is typically needed for the majority of tool uses. In other words, accommodating the high startup torque in a power tool driven by an IPM motor comes at the expense of an increased tool size, cost, and efficiency.

[0046] More specifically, in order to increase the torque capabilities (e.g., the startup torque) of the BLDC motor, the motor size is increased (e.g., motor diameter or motor length is increased). However, increasing the BLDC motor size adds to the overall power tool size and cost. In addition, increasing the size of the BLDC motor to accommodate the worst-case load scenario (e.g., startup conditions) will result in an oversized motor for the remaining majority of the power tools operational needs (e.g., non-startup conditions). Finally, increasing the startup torque capability of the BLDC motor has the counterproductive effect of also decreasing the no-load speed. Decreasing the no-load speed is undesirable because once the motor has reached operational speeds, it is desirable to operate the motor as fast as possible in order to complete the task as fast as possible.

[0047] With reference to FIG. 5, the power tools 10, 14, 18 include a motor assembly positioned within the housings 12, 16, 20. In the illustrated embodiment, the motor assembly is a permanent magnet synchronous reluctance machine (PMSRM) 74. In other words, the power tools 10, 14, 18 include a permanent magnet synchronous reluctance machine 74 positioned within each of the housings 12, 16, 20 and operable to drive the tool element. In particular, FIG. 5 illustrates a cross-sectional view of the PMSRM 74. The permanent magnet synchronous reluctance machine (PMSRM) 74 may also be referred to a permanent magnet assisted synchronous reluctance machine (PMaSRM), a permanent magnet synchronous reluctance motor, or a permanent magnet assisted synchronous reluctance motor. The permanent magnet synchronous reluctance machine 74 is operable as either a motor or a generator.

[0048] The PMSRM 74 includes a stator 78 and a rotor 82. The stator 78 includes a stator body 86 with teeth 90, which define windings slots 94 that receive stator windings 98. In the illustrated embodiment, the teeth 90 extend radially inward. In some embodiments, the stator body 86 is a single solid ferromagnetic piece. In other embodiments, the stator body 86 is formed as a stack of stator laminations. In the illustrated embodiment, the stator 78 includes twenty four winding slots 94. In other embodiments, the stator 78 includes 25 or greater winding slots 94. In other embodiments, the stator 78 includes 23 or fewer winding slots 94. In some embodiments, the stator includes six or more winding slots 94. The stator windings may be distributed windings that span multiple teeth 90, which allows for multiple winding slots 94 to be used per pole. In some embodiments, the stator includes twelve or more winding slots 94.

[0049] With continued reference to FIG. 5, the rotor 82 includes a rotor body 102 with curved slots 106A, 106B, 106C (i.e., arcuate slots) formed in the rotor body 102. In some embodiments, the rotor body 102 is a single solid ferromagnetic piece. In other embodiments the rotor body 102 is formed as a stack of rotor laminations. The rotor 82 includes a first slot 106A, a second slot 106B and a third slot 106C. The first slot 106A is a different size than the second slot 106B, and the second slot 106B is a different size than the third slot 106C. In the illustrated embodiment, the first slot 106A is larger than the second slot 106B and the second slot 106B is larger than the third slot 106C. The rotor body 102, in the illustrated embodiment, includes four sets of the three slots 106A, 106B, 106C (i.e., a total of twelve slots). In other words, the rotor 82 is a 4-pole rotor. In other embodiments, the rotor 82

include 5 or more poles. In further alternative embodiments, the rotor 82 includes 3 or fewer poles. The slots 106A, 106B, 106C are operable as flux barriers. In the illustrated embodiment, portions of the slots 106A, 106B, 106C are empty and are configured as air flux barriers. In other embodiments, the slots 106A, 106B, 106C is at least partially filled with a flux barrier material. In some embodiments, two or fewer slots are define each rotor pole.

[0050] In addition, the rotor 82 includes permanent magnets 110A, 110B, 110C positioned within the slots 106A, 106B, 106C. In the illustrated embodiment, the permanent magnets 110A, 110B, 110C are curved to correspond to the arcuate shape of the slots 106A, 106B, 106C. The magnet material may include sintered or bonded ferrites, ceramic ferrites, ceramics, neodymium iron boron (NdFeB). Bonded neodymium can be injected molded into slots from a front of the motor, whereas sintered neodymium is cut from a single block of material. With bonded neodymium, the material can be magnetized after injection, which greatly improves manufacturability and creates less waste. In addition, plastic inserts in magnet slots can be used to achieve less than 100% slot fill, which provides cost savings while still allowing for electrical functionality.

[0051] With reference to FIG. 6, the first slot 106A is positioned a first distance R1 from a center 112 of the rotor body 102, the second slot 106B is positioned a second distance R2 from the center 112, and the third slot 106C is positioned a third distance R3 from the center 112. The center 112 in the illustrated embodiment is the rotational axis of the rotor 82. The first slot 106A, the second slot 106B, and the third slot 106C are curved about a common point 107. In other words, the second slot 106B is partially nested within the first slot 106A and the third slot 106C is partially nested within the second slot 106B. In the illustrated embodiment, the common point 107 is positioned outside of the rotor body 102. Specifically, the common point 107 is located on a tooth 90 of the stator 78. In other words, the slots 106A, 106B, 106C are concave and curve about the point 107 positioned radially outward from an outer circumferential surface 103 of the rotor body 102.

[0052] With continued reference to FIG. 6, the ends of the slots 106A, 106B, 106C are spaced an equal distance away from the outer circumferential surface 103 of the rotor body 102. For example, a first dimension D1 measured between a first end 108A of the first slot 106A and the outer circumferential surface 103 is approximately the same distance as a second dimension D2 measured between a second end 108B of the first slot 106A and the outer circumferential surface 103. Likewise, a third dimension D3 measured between a first

end 108C of the second slot 106B and the outer circumferential surface 103 is approximately the same distance as the first dimension D1. In other words, a distance D1-D6 from any end 108A-108D of each of the slots 106A, 106B, 106C is positioned approximately the same distance from the outer circumferential surface 103 of the rotor body 102.

[0053] With continued reference to FIG. 6, the first magnet 110A is positioned within the first slot 106A, the second magnet 110B is positioned within the second slot 106B, and a third magnet 110C is positioned within the third slot 106C. In the illustrated embodiment, the magnets 110A, 110B, 110C are positioned in the center of the slots 106A, 106B, 106C, respectively. The magnets 110A, 110B, 110C do not fill the entire slots 106A, 106B, 106C. For example, the first slot 106A has a span S1 of approximately 110 degrees about the common point 107 and the first magnet 110A has a span S2 of approximately 58 degrees about the common point 107. As such, the first magnet 110A spans within a range of approximately 50% to approximately 56% of the first slot 106A span. In the illustrated embodiment, the first magnet 110A spans approximately 53% of the first slot 106A span. Likewise, the second slot 106B has a span S3 of approximately 103 degrees about the common point 107 and the second magnet 110B has a span S4 of approximately 37 degrees about the common point 107. As such, the second magnet 110B spans within a range of approximately 33% to approximately 39% of the second slot 106B span. In the illustrated embodiment, the second magnet 110B spans approximately 36% of the section slot 106B span. Similarly, the third slot 106C has a span S5 of approximately 81 degrees about the common point 107 and the third magnet 110C has a span S6 of approximately 31 degrees about the common point 107. As such, the third magnet 110C spans within a range of approximately 35% to approximately 41% of the third slot 106C span. In the illustrated embodiment, the third magnet 110C spans approximately 38% of the third slot 106C span. As such, the magnet 110A-110C within each of the plurality of slots 106A-106C span less than approximately 56% of the slot.

[0054] With reference to FIG. 6A, the rotor 82A includes a rotor body 102 with curved slots 106A, 106B, 106C (i.e., arcuate slots) formed in the rotor body 102. The rotor 82A is similar to the rotor 82 of FIG. 6 with similar reference numerals use to identify similar structure. The rotor 82A differs from the rotor 82 in that the rotor 82A includes permanent magnets 111A, 111B, 111C positioned within the entirety of the slots 106A, 106B, 106C. In the illustrated embodiment, the permanent magnets 110A, 110B, 110C are curved to

correspond to the arcuate shape of the slots 106A, 106B, 106C and span 100% of the slot spans S1, S2, S3. In other words, the magnet 111A extends from end 108A to the end 108B of the slot 106A. Likewise, the magnet 111B extends from end 108C to the end 108D of the slot 106B and the magnet 111C extends from end 108E to the end 108F of the slot 106C. In other embodiments, the magnets 111A, 111B, 111C may span less than 100% of the corresponding slots 106A, 106B, 106C.

[0055] With reference to FIG. 7, the capabilities of the PMSRM 74 are compared to the conventional IPM motor having of the same size. In other words, the comparison between the PMSRM 74 and the conventional IPM motor is made with motors having the same package size (i.e., volumetric space). First, an IPM motor speed 114 is compared to the PMSRM speed 118. The PMSRM speed 118 is higher than the IPM motor speed 114 at low torque (i.e., no-load conditions). In the illustrated embodiment, the PMSRM speed 118 at low torque is approximately 30% more than the IPM motor speed 114 at low torque. Second, an IPM motor power 122 is compared to the PMSRM power 126. The PMSRM power 126 is higher than the IPM power 122 at high torque levels because the PMSRM 74 is capable of producing more torque than the similarly sized IPM motor. In the illustrated embodiment, the PMSRM 74 produces approximately 25% more torque than the IPM motor. Third, an IPM motor efficiency 130 is compared to the PMSRM efficiency 134. The PMSRM efficiency 134 is higher than the IPM motor efficiency 130 at high torque conditions, and the PMSRM efficiency 134 is similar to the IPM motor efficiency 130 at low torque conditions. As such, the PMSRM 74 provides relevant speed, torque, power, and efficiency benefits when compared to the conventional IPM motor with the same package size.

[0056] The power tool 10, 14, 18 that includes the PMSRM 74 allows for improvement at two important operating conditions (i.e., the start-up torque and the no-load speed) without unnecessarily adding size and cost when compared to other BLDC motor types, including IPM motors, with the same package size. With the PMSRM 74, the power tool can be made smaller if desirable, or the extra torque capabilities can add a margin of success for extreme startup scenarios (e.g., for cold startups where the hydraulic fluid being pumped is less viscous). The permanent magnet synchronous reluctance motor 74 provides more startup torque than a BLDC motor with a same package size and provides a higher no-load speed than the BLDC motor with the same package size.

[0057] In addition to the improved operating characteristics, the PMSRM 74 includes less rare earth magnet material compared to a comparable IPM design. In some embodiments, the PMSRM 74 includes 50% of the magnets included in the conventional IPM design with the same package size. Magnet material is expensive and is subject to volatile financial markets. As such, reducing the required magnet material is desirable for long term cost and planning.

[0058] Although the disclosure has been described in detail with reference to certain preferred embodiments, variations and modifications exist within the scope and spirit of one or more independent aspects of the disclosure as described. Various features and advantages are set forth in the following claims.

CLAIMS

What is claimed is:

1. A power tool comprising:
 - a housing;
 - a motor assembly positioned within the housing, the motor assembly including:
 - a stator with winding slots that receive stator windings, and
 - a rotor including a rotor body with a first slot positioned a first distance from a center of the rotor body and a second slot positioned a second distance from the center of the rotor body, the first slot and the second slot are each curved about a common point;
 - wherein the rotor further includes a first magnet positioned within the first slot and a second magnet positioned within the second slot.
2. The power tool of claim 1, wherein the common point is positioned outside of the rotor body.
3. The power tool of claim 1, wherein:
 - a first dimension is measured between a first end of the first slot and an outer circumferential surface of the rotor body;
 - a second dimension is measured between a second end of the first slot and the outer circumferential surface of the rotor body; and
 - the second dimension is equal to the first dimension.
4. The power tool of claim 1, wherein:
 - a first dimension is measured between an end of the first slot and an outer circumferential surface of the rotor body;
 - a second dimension is measured between an end of the second slot and the outer circumferential surface of the rotor body; and
 - the second dimension is equal to the first dimension.
5. The power tool of claim 1, wherein the first magnet spans within a range of 50% to 100% of the first slot.

6. The power tool of claim 5, wherein the first magnet spans within a range of 50% to 56% of the first slot.
7. The power tool of claim 6, wherein the first magnet spans 53% of the first slot.
8. The power tool of claim 1, wherein the second magnet spans within a range of 33% to 100% of the second slot.
9. The power tool of claim 8, wherein the second magnet spans within a range of 33% to 39% of the second slot.
10. The power tool of claim 9, wherein the second magnet spans 36% of the second slot.
11. The power tool of claim 1, wherein the rotor further includes a third slot positioned a third distance from the center of the rotor body, the third slot curved about the common point; and a third magnet positioned within the third slot.
12. The power tool of claim 11, wherein the third magnet spans within a range of 35% to 100% of the third slot.
13. The power tool of claim 12, wherein the third magnet spans within a range of 35% to 41% of the third slot.
14. The power tool of claim 13, wherein the third magnet spans 38% of the third slot.
15. The power tool of claim 1, wherein the motor is configured to drive a cyclical load.
16. The power tool of claim 1, wherein the motor provides more startup torque than a brushless DC motor with a same package size and provides a higher no-load speed than the brushless DC motor with the same package size.
17. The power tool of claim 1, further comprising a tool element and wherein the tool element is driven by the motor.

18. The power tool of claim 1, wherein the stator includes at least twenty-four slots.
19. The power tool of claim 1, wherein the rotor is a 4-pole rotor.
20. A power tool comprising:
 - a housing;
 - a permanent magnet synchronous reluctance machine positioned within the housing, the permanent magnet synchronous reluctance machine including a stator with stator windings and a rotor with a plurality of slots and a magnet positioned within each of the plurality of slots; and
 - a tool element driven by the permanent magnet synchronous reluctance machine.
21. The power tool of claim 20, wherein the permanent magnet synchronous reluctance machine provides more startup torque than a brushless DC motor with a same package size and provides higher no-load speed than the brushless DC motor with the same package size.
22. The power tool of claim 20, wherein the plurality of slots are curved.
23. The power tool of claim 22, wherein the magnet within each of the plurality of slots span less than 56% of the slot.
24. The power tool of claim 20, wherein the permanent magnet synchronous reluctance machine includes at least twenty-four winding slots formed in the stator and the rotor includes at least four poles.
25. A motor assembly for a power tool, the motor assembly comprising:
 - a stator with winding slots that receive stator windings; and
 - a rotor including a rotor body with a first slot positioned a first distance from a center of the rotor body and a second slot positioned a second distance from the center of the rotor body; the first slot and the second slot are each curved about a common point;
 - wherein the rotor further includes a first magnet positioned within the first slot and a second magnet positioned within the second slot.

26. The motor assembly of claim 25, wherein the common point is positioned outside of the rotor body.
27. The motor assembly of claim 25, wherein:
a first dimension is measured between a first end of the first slot and an outer circumferential surface of the rotor body;
a second dimension is measured between a second end of the first slot and the outer circumferential surface of the rotor body; and
the second dimension is equal to the first dimension.
28. The motor assembly of claim 25, wherein:
a first dimension is measured between an end of the first slot and an outer circumferential surface of the rotor body;
a second dimension is measured between an end of the second slot and the outer circumferential surface of the rotor body; and
the second dimension is equal to the first dimension.
29. The motor assembly of claim 25, wherein the first magnet spans within a range of 50% to 100% of the first slot.
30. The motor assembly of claim 29, wherein the first magnet spans 53% of the first slot.
31. The motor assembly of claim 25, wherein the second magnet spans within a range of 33% to 100% of the second slot.
32. The motor assembly of claim 31, wherein the second magnet spans 36% of the second slot.
33. The power tool of claim 25, wherein the rotor further includes a third slot positioned a third distance from the center of the rotor body, the third slot curved about the common point; and a third magnet positioned within the third slot.
34. The motor assembly of claim 33, wherein the third magnet spans within a range of 35% to 100% of the third slot.

35. The motor assembly of claim 34, wherein the third magnet spans 38% of the third slot.
36. The motor assembly of claim 25, wherein the motor is configured to drive a cyclical load.
37. The motor assembly of claim 25, wherein the motor provides more startup torque than a brushless DC motor with a same package size and provides a higher no-load speed than the brushless DC motor with the same package size.
38. The motor assembly of claim 25, further comprising a tool element and wherein the tool element is driven by the motor.
39. The motor assembly of claim 25, wherein the stator includes at least twenty-four slots.
40. The motor assembly of claim 25, wherein the rotor is a 4-pole rotor.

1/6

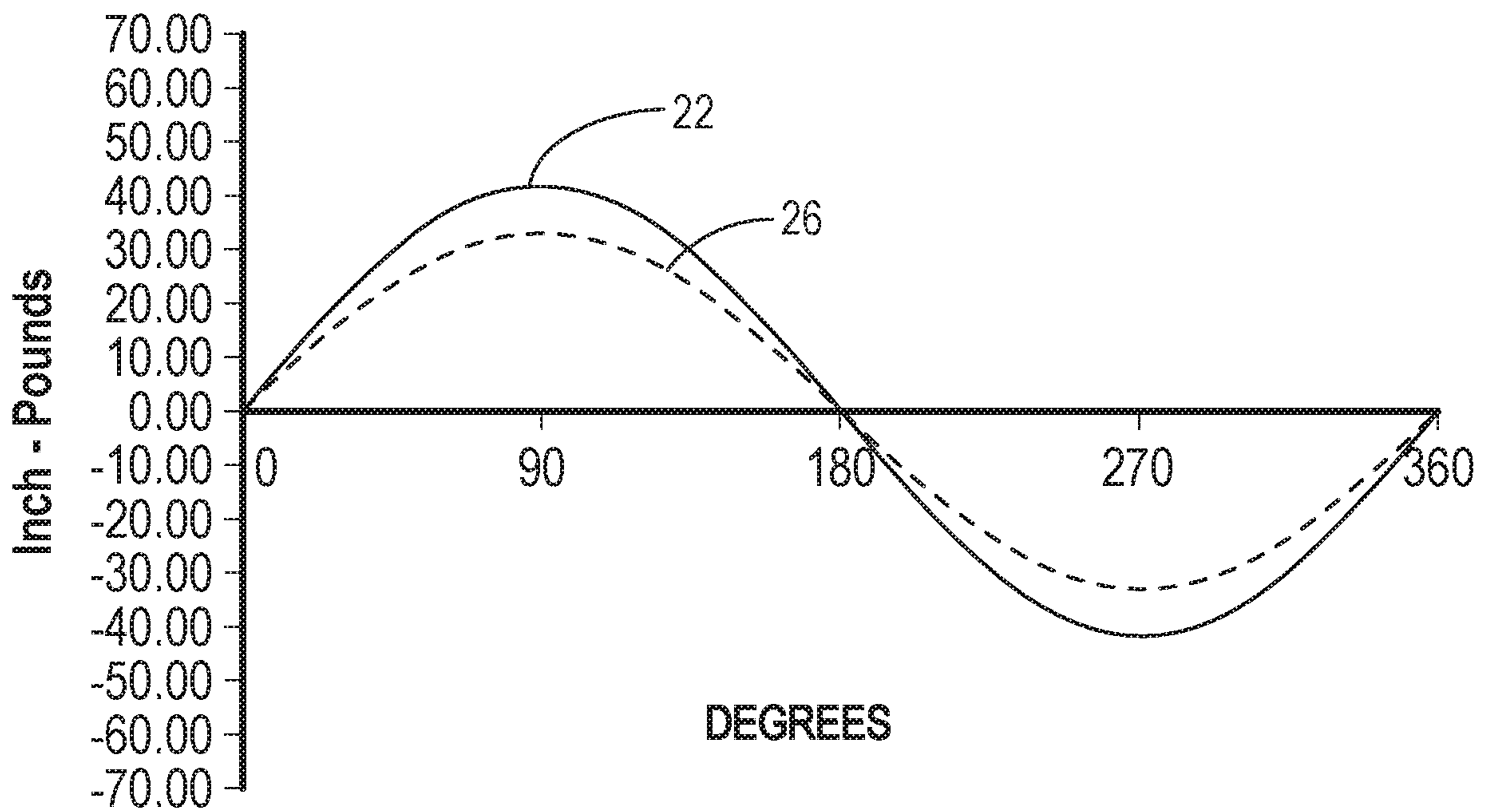
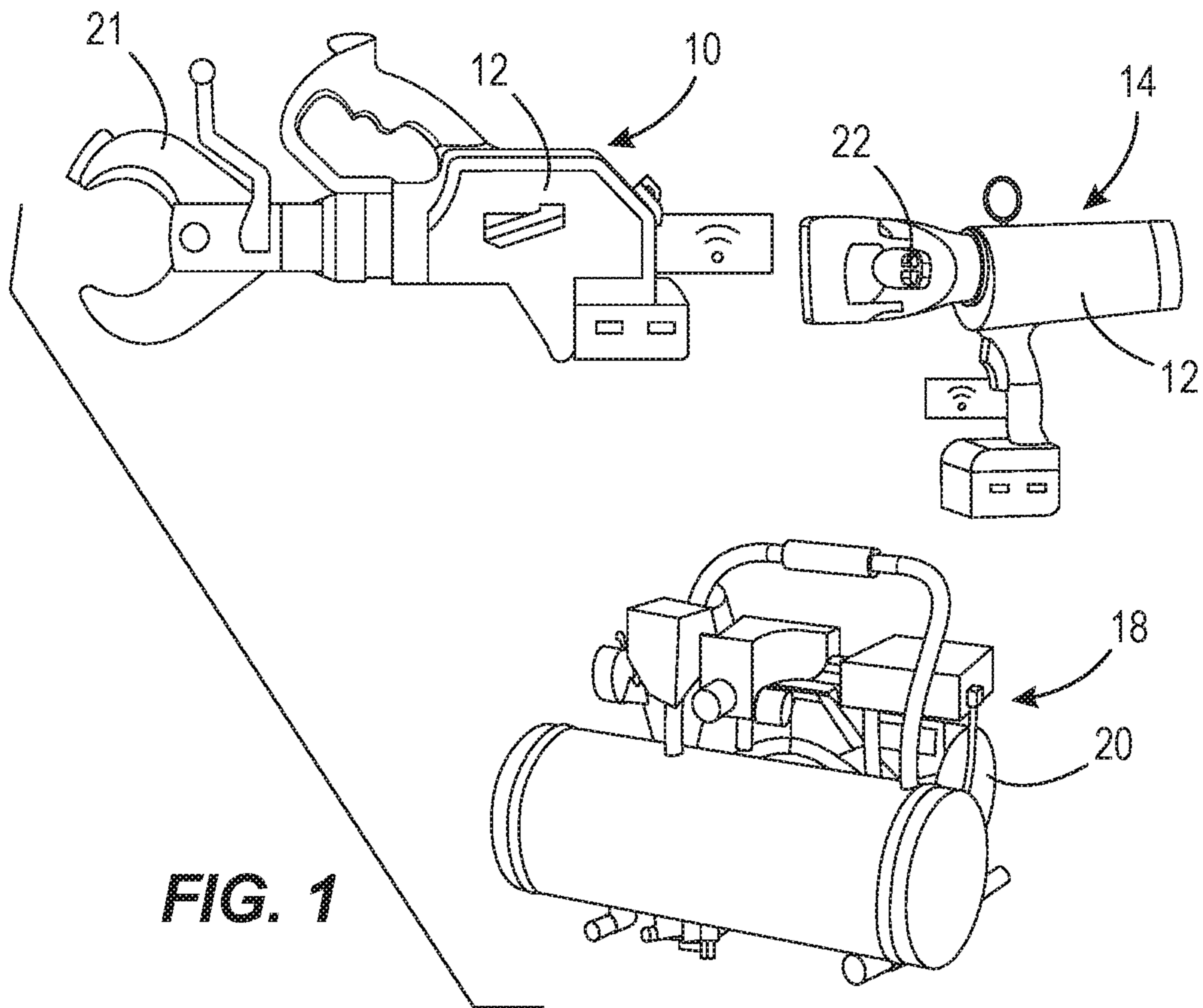


FIG. 2

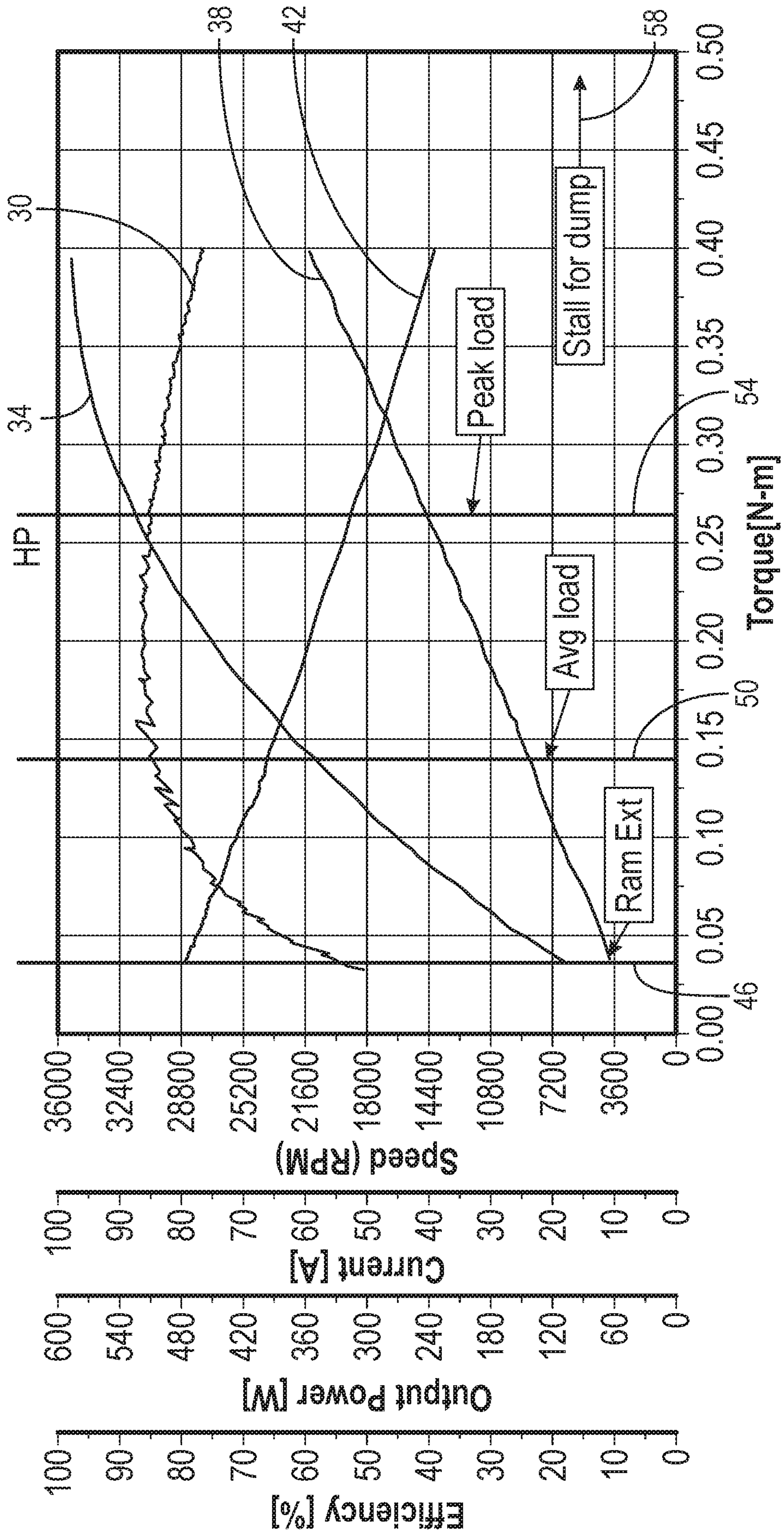


FIG. 3

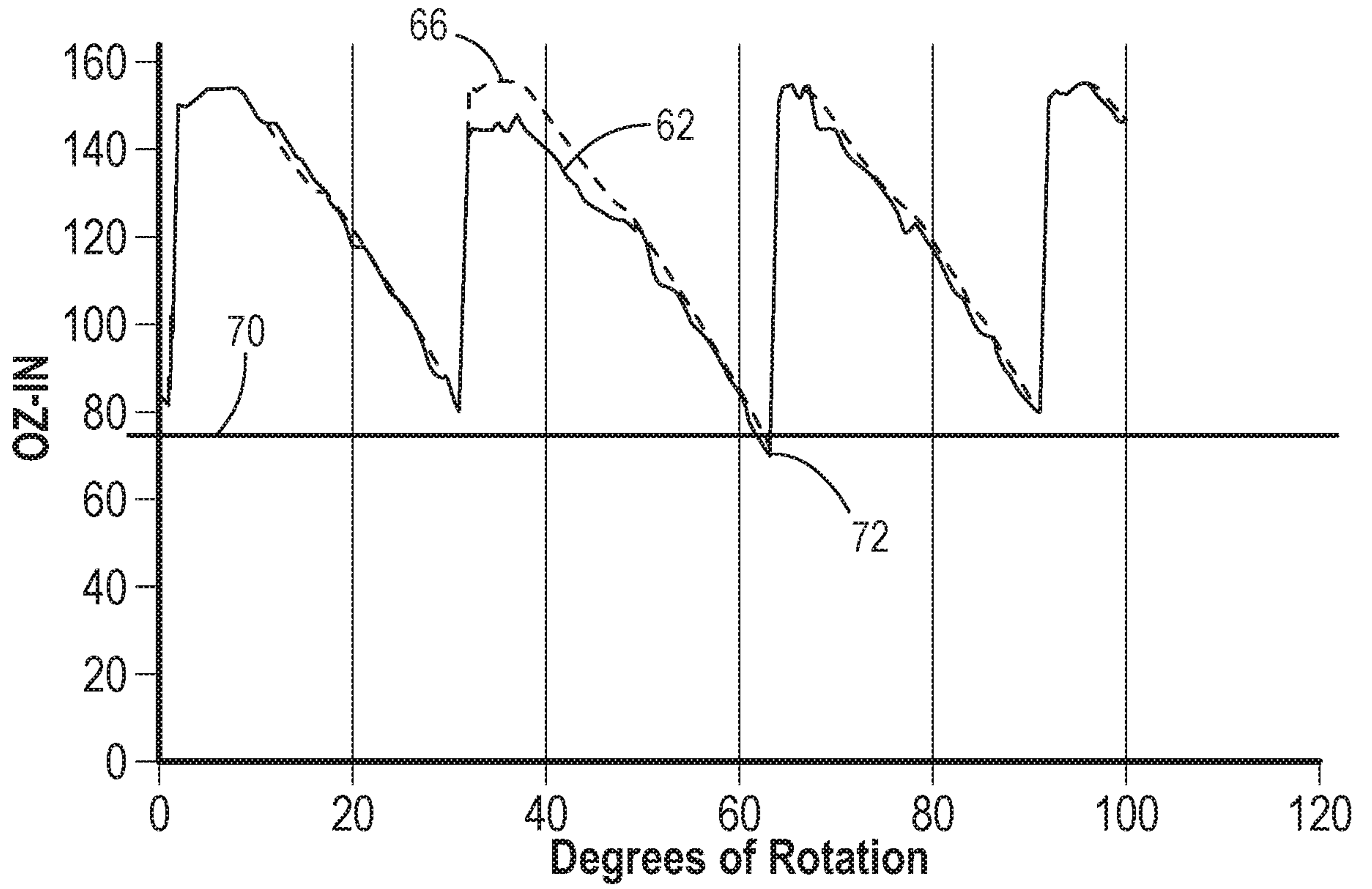
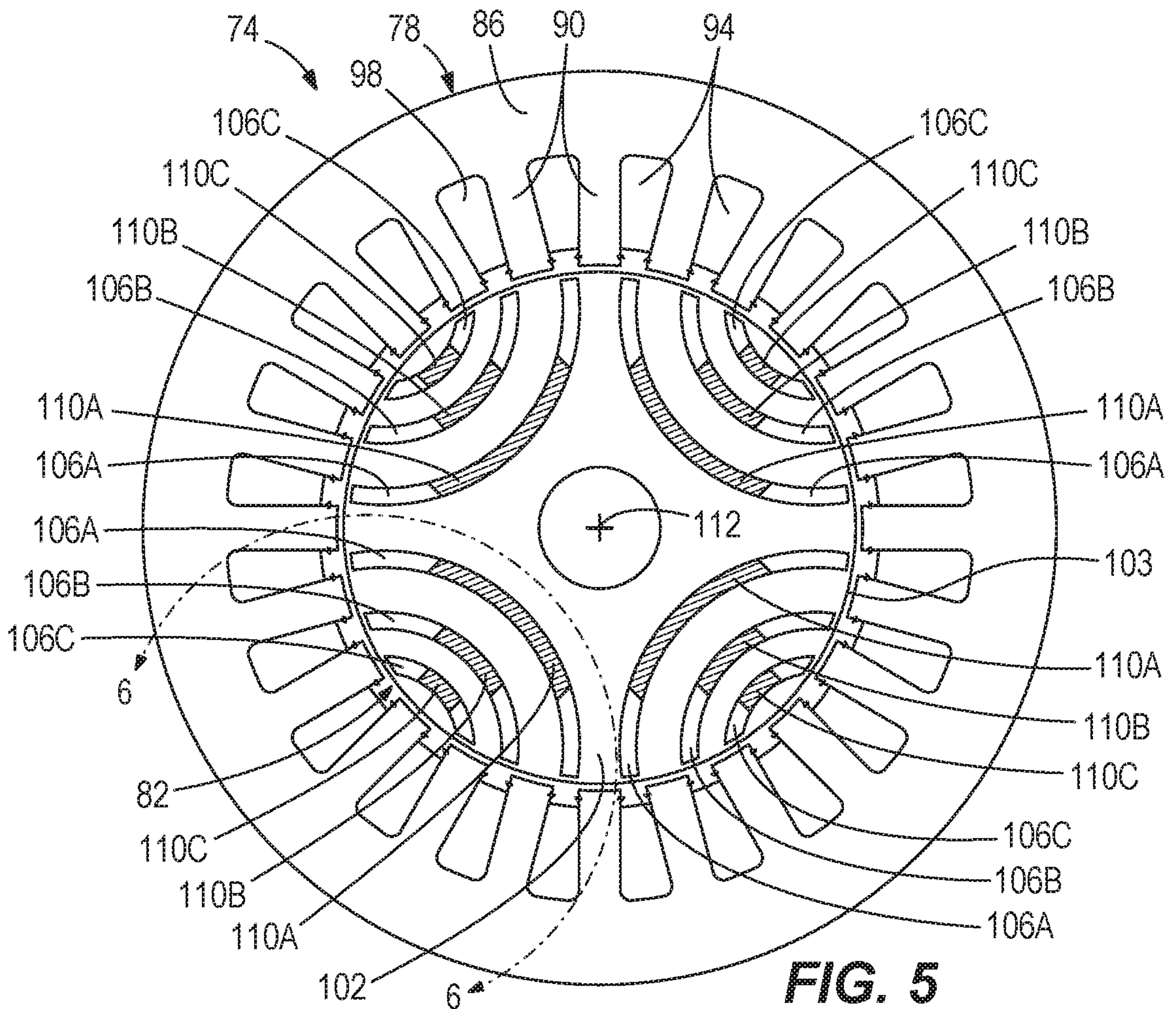


FIG. 4



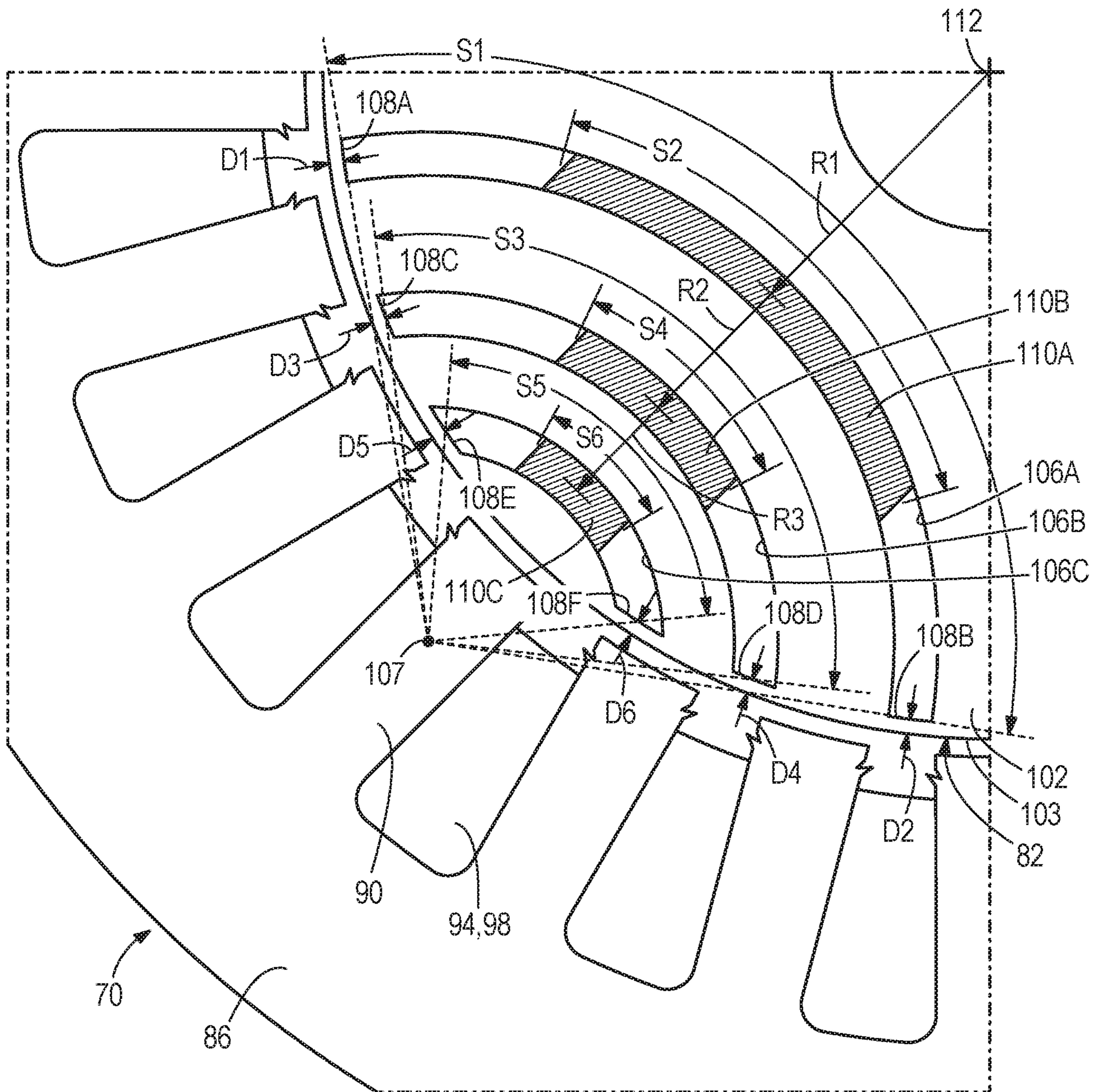


FIG. 6

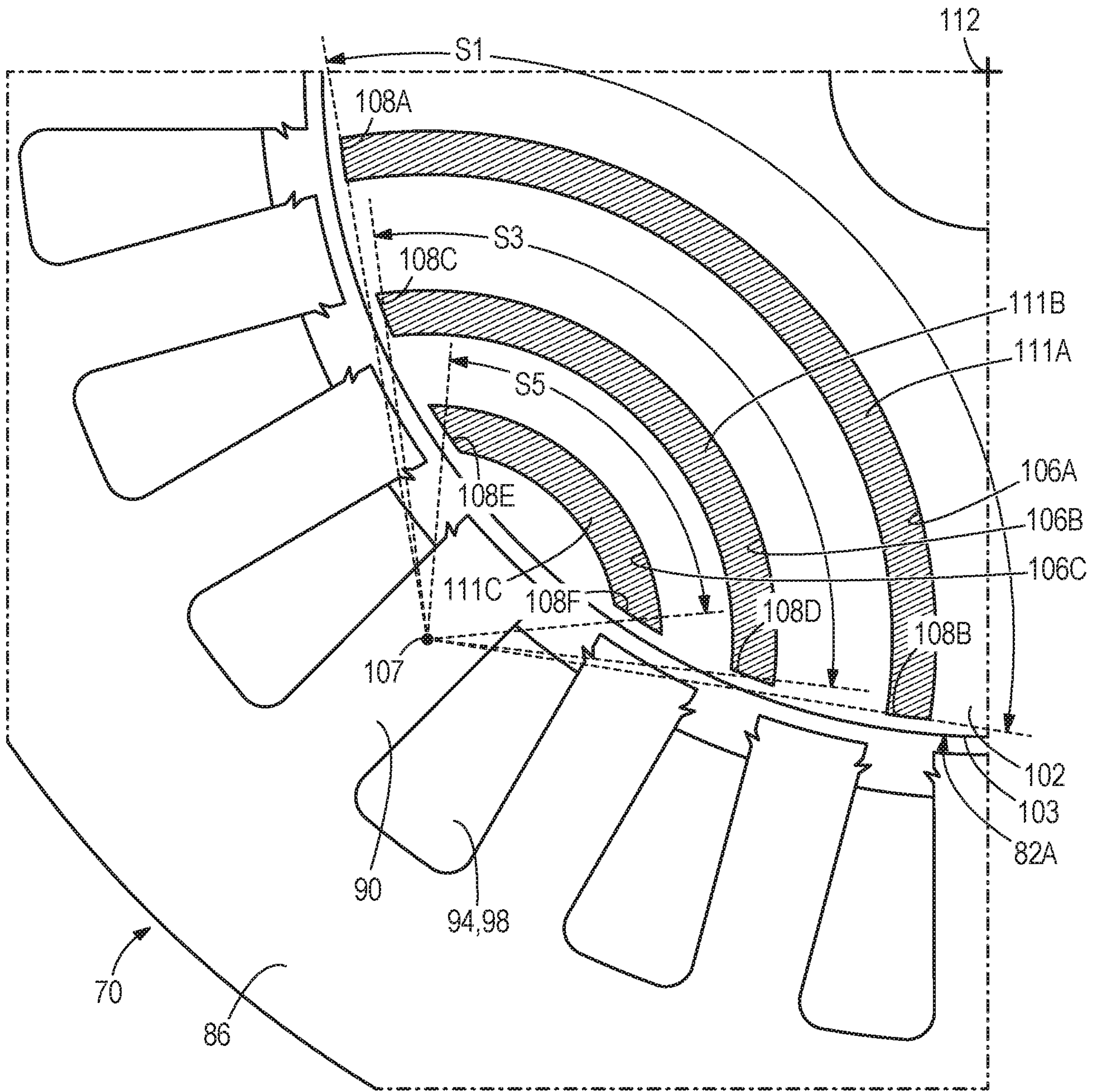


FIG. 6A

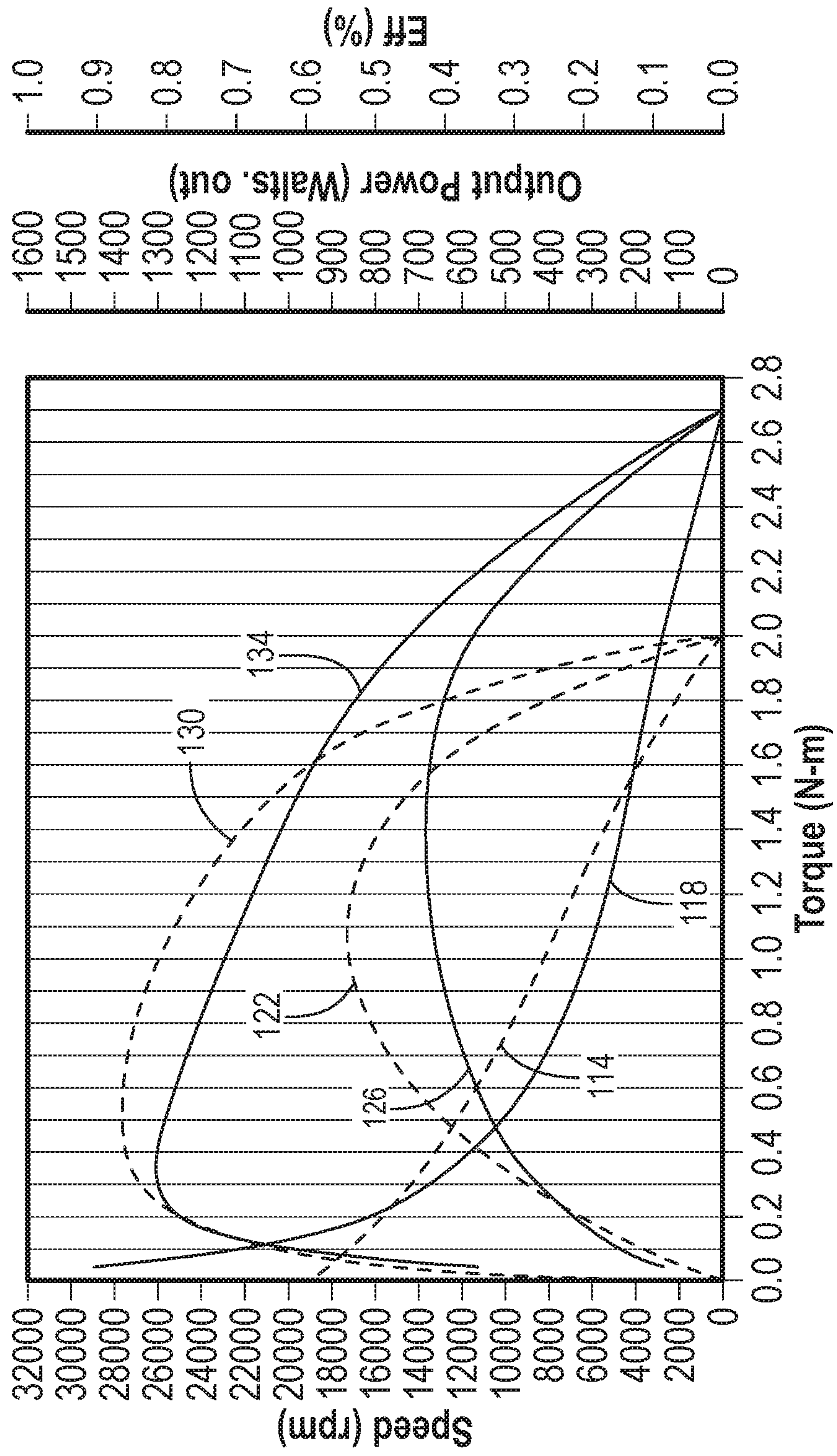


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2020/056568

<p>A. CLASSIFICATION OF SUBJECT MATTER</p> <p>H02K 1/24(2006.01)i; H02K 1/16(2006.01)i; H02K 1/27(2006.01)i; H02K 3/12(2006.01)i; H02K 29/00(2006.01)i; B25F 5/00(2006.01)i; H02K 7/14(2006.01)i</p> <p>According to International Patent Classification (IPC) or to both national classification and IPC</p>																																						
<p>B. FIELDS SEARCHED</p> <p>Minimum documentation searched (classification system followed by classification symbols)</p> <p>H02K 1/24(2006.01); H02K 1/16(2006.01); H02K 1/22(2006.01); H02K 1/27(2006.01); H02K 19/10(2006.01); H02K 21/16(2006.01)</p> <p>Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched</p> <p>Korean utility models and applications for utility models Japanese utility models and applications for utility models</p> <p>Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)</p> <p>eKOMPASS(KIPO internal) & keywords: power tool, motor, magnet, reluctance, slot</p>																																						
<p>C. DOCUMENTS CONSIDERED TO BE RELEVANT</p> <table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th style="width:10%;">Category*</th> <th style="width:70%;">Citation of document, with indication, where appropriate, of the relevant passages</th> <th style="width:20%;">Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td style="text-align:center;">X</td> <td>US 2015-0303749 A1 (MITSUBA CORPORATION) 22 October 2015 (2015-10-22) See paragraphs [0052], [0061]-[0063]; and figures 2-5.</td> <td style="text-align:center;">1-2,5-19,25-26,29-40</td> </tr> <tr> <td style="text-align:center;">Y</td> <td></td> <td style="text-align:center;">3-4,20-24,27-28</td> </tr> <tr> <td colspan="3" style="border-top: 1px dashed black;"></td> </tr> <tr> <td style="text-align:center;">Y</td> <td>US 2019-0068036 A1 (ABB SCHWEIZ AG.) 28 February 2019 (2019-02-28) See paragraph [0017]; and figure 3.</td> <td style="text-align:center;">3-4,20-24,27-28</td> </tr> <tr> <td colspan="3" style="border-top: 1px dashed black;"></td> </tr> <tr> <td style="text-align:center;">A</td> <td>US 2018-0138765 A1 (D&M HOLDING S.P.A.) 17 May 2018 (2018-05-17) See the entire document.</td> <td style="text-align:center;">1-40</td> </tr> <tr> <td colspan="3" style="border-top: 1px dashed black;"></td> </tr> <tr> <td style="text-align:center;">A</td> <td>KR 10-2014-0143799 A (MITSUBISHI ELECTRIC CORP.) 17 December 2014 (2014-12-17) See the entire document.</td> <td style="text-align:center;">1-40</td> </tr> <tr> <td colspan="3" style="border-top: 1px dashed black;"></td> </tr> <tr> <td style="text-align:center;">A</td> <td>JP 2002-010594 A (TOYO ELECTRIC MFG. CO., LTD.) 11 January 2002 (2002-01-11) See the entire document.</td> <td style="text-align:center;">1-40</td> </tr> <tr> <td colspan="3" style="border-top: 1px dashed black;"></td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	X	US 2015-0303749 A1 (MITSUBA CORPORATION) 22 October 2015 (2015-10-22) See paragraphs [0052], [0061]-[0063]; and figures 2-5.	1-2,5-19,25-26,29-40	Y		3-4,20-24,27-28				Y	US 2019-0068036 A1 (ABB SCHWEIZ AG.) 28 February 2019 (2019-02-28) See paragraph [0017]; and figure 3.	3-4,20-24,27-28				A	US 2018-0138765 A1 (D&M HOLDING S.P.A.) 17 May 2018 (2018-05-17) See the entire document.	1-40				A	KR 10-2014-0143799 A (MITSUBISHI ELECTRIC CORP.) 17 December 2014 (2014-12-17) See the entire document.	1-40				A	JP 2002-010594 A (TOYO ELECTRIC MFG. CO., LTD.) 11 January 2002 (2002-01-11) See the entire document.	1-40			
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.																																				
X	US 2015-0303749 A1 (MITSUBA CORPORATION) 22 October 2015 (2015-10-22) See paragraphs [0052], [0061]-[0063]; and figures 2-5.	1-2,5-19,25-26,29-40																																				
Y		3-4,20-24,27-28																																				
Y	US 2019-0068036 A1 (ABB SCHWEIZ AG.) 28 February 2019 (2019-02-28) See paragraph [0017]; and figure 3.	3-4,20-24,27-28																																				
A	US 2018-0138765 A1 (D&M HOLDING S.P.A.) 17 May 2018 (2018-05-17) See the entire document.	1-40																																				
A	KR 10-2014-0143799 A (MITSUBISHI ELECTRIC CORP.) 17 December 2014 (2014-12-17) See the entire document.	1-40																																				
A	JP 2002-010594 A (TOYO ELECTRIC MFG. CO., LTD.) 11 January 2002 (2002-01-11) See the entire document.	1-40																																				
<p><input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.</p>																																						
<table style="width:100%; border: none;"> <tr> <td style="width:50%; border: none;"> <p>* Special categories of cited documents:</p> <p>“A” document defining the general state of the art which is not considered to be of particular relevance</p> <p>“D” document cited by the applicant in the international application</p> <p>“E” earlier application or patent but published on or after the international filing date</p> <p>“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)</p> <p>“O” document referring to an oral disclosure, use, exhibition or other means</p> <p>“P” document published prior to the international filing date but later than the priority date claimed</p> </td> <td style="width:50%; border: none;"> <p>“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</p> <p>“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</p> <p>“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</p> <p>“&” document member of the same patent family</p> </td> </tr> </table>			<p>* Special categories of cited documents:</p> <p>“A” document defining the general state of the art which is not considered to be of particular relevance</p> <p>“D” document cited by the applicant in the international application</p> <p>“E” earlier application or patent but published on or after the international filing date</p> <p>“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)</p> <p>“O” document referring to an oral disclosure, use, exhibition or other means</p> <p>“P” document published prior to the international filing date but later than the priority date claimed</p>	<p>“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</p> <p>“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</p> <p>“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</p> <p>“&” document member of the same patent family</p>																																		
<p>* Special categories of cited documents:</p> <p>“A” document defining the general state of the art which is not considered to be of particular relevance</p> <p>“D” document cited by the applicant in the international application</p> <p>“E” earlier application or patent but published on or after the international filing date</p> <p>“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)</p> <p>“O” document referring to an oral disclosure, use, exhibition or other means</p> <p>“P” document published prior to the international filing date but later than the priority date claimed</p>	<p>“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</p> <p>“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</p> <p>“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</p> <p>“&” document member of the same patent family</p>																																					
<p>Date of the actual completion of the international search</p> <p align="center">03 February 2021</p>	<p>Date of mailing of the international search report</p> <p align="center">03 February 2021</p>																																					
<p>Name and mailing address of the ISA/KR</p> <p align="center">Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea</p> <p>Facsimile No. +82-42-481-8578</p>	<p>Authorized officer</p> <p align="center">KANG MIN JEONG</p> <p>Telephone No. +82-42-481-8131</p>																																					

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2020/056568

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	2015-0303749	A1	22 October 2015	BR	112015003256	A2	24 April 2018
				CN	104508948	A	08 April 2015
				CN	104508948	B	25 August 2017
				EP	2887503	A1	24 June 2015
				EP	2887503	B1	14 November 2018
				JP	2014-039399	A	27 February 2014
				JP	2014-093914	A	19 May 2014
				JP	5975786	B2	23 August 2016
				US	9490673	B2	08 November 2016
				WO	2014-027630	A1	20 February 2014
US	2019-0068036	A1	28 February 2019	US	10673311	B2	02 June 2020
				WO	2019-040097	A1	28 February 2019
US	2018-0138765	A1	17 May 2018	AU	2016-268372	A1	01 December 2016
				AU	2016-268372	B2	14 May 2020
				AU	2016-269006	A1	01 December 2016
				AU	2016-269006	B2	25 June 2020
				CN	107787546	A	09 March 2018
				CN	107820525	A	20 March 2018
				CN	107820525	B	15 February 2019
				CN	107849772	A	27 March 2018
				CN	107849772	B	03 July 2020
				CN	108064331	A	22 May 2018
				EP	3298282	A1	28 March 2018
				EP	3298283	A1	28 March 2018
				EP	3298336	A1	28 March 2018
				EP	3298336	B1	22 May 2019
				EP	3298681	A1	28 March 2018
				JP	2016-220211	A	22 December 2016
				JP	2018-522146	A	09 August 2018
				JP	2018-522797	A	16 August 2018
				JP	6751413	B2	02 September 2020
				KR	10-2018-0016401	A	14 February 2018
				KR	10-2018-0022675	A	06 March 2018
				US	10215295	B2	26 February 2019
				US	10707733	B2	07 July 2020
				US	10724528	B2	28 July 2020
				US	2018-0149159	A1	31 May 2018
				US	2018-0156223	A1	07 June 2018
				US	2018-0163881	A1	14 June 2018
				US	2018-0346385	A1	06 December 2018
				US	9924274	B2	20 March 2018
				WO	2016-189433	A1	01 December 2016
				WO	2016-189445	A1	01 December 2016
				WO	2016-189453	A1	01 December 2016
				WO	2016-189454	A1	01 December 2016
				ZA	201708312	B	28 November 2018
KR	10-2014-0143799	A	17 December 2014	CN	104247214	A	24 December 2014
				CN	104247214	B	24 May 2017
				EP	2843802	A1	04 March 2015
				EP	2843802	B1	01 August 2018

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No. PCT/US2020/056568

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
		KR 10-1624070 B1	24 May 2016
		US 2015-0077034 A1	19 March 2015
		US 9685829 B2	20 June 2017
		WO 2013-160988 A1	31 October 2013
<hr/>			
JP 2002-010594 A	11 January 2002	None	
<hr/>			