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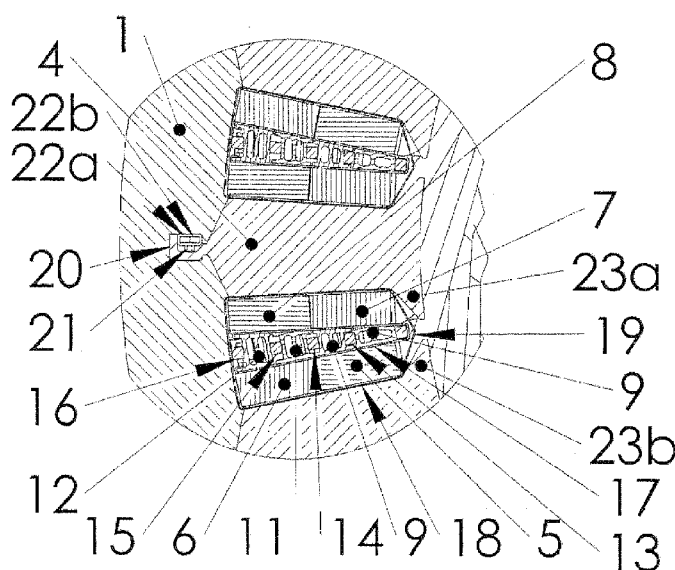
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(54) Title: LIQUID COOLED STATOR FOR HIGH EFFICIENCY MACHINE



(57) Abstract: A stator for a motor, generator or the like that is liquid cooled using glycol or similar fluid with the cooling applied directly in the winding slots of the stator in either concentrated wound or distributed wound configurations. Stators for rotary electric machines including electric motors, generators, and the like have employed various types of cooling including air, liquid and two phase cooling. Air blown through the center of the machine had traditionally been the standard with liquid becoming more common in high power applications.

**LIQUID COOLED STATOR
FOR HIGH EFFICIENCY MACHINE**

Related Application

This application claims the benefit of U.S. Patent Application Serial No. 13/855,801, filed April 3, 2013, the disclosures of which are entirely incorporated herein by reference.

Technical Field

The present invention relates generally to electric motors and generators, and in particular to a liquid cooled stator for an electric motor or generator.

Background

Stators for rotary electric machines including electric motors, generators, and the like have employed various types of cooling including air, liquid and two phase cooling. Air blown through the center of the machine had traditionally been the standard with liquid becoming more common in high power applications. Two phase cooling has not developed into a mainstream due to cost and complexity. Liquid cooling is preferred for many high power applications because it generates a more compact design and is compatible with a sealed housing construction which is preferable in many environments.

The most common liquid cooling design uses a cooling jacket wrapped around the outside of the stator assembly. This can be seen in U.S. patent 5,448,118 entitled LIQUID COOLED MOTOR AND ITS JACKET, included herein by reference. In this design there is an aluminum extrusion that surrounds the outside of the stator and has passages for cooling fluid to pass through. This design cools the stator better than air, but is limited by i) the conductivity between the jacket and the stator, ii) the poor conductivity of the stator laminations, iii) the conductivity of the slot liners, and iv) the poor conductivity between the winding and the slot liners.

Another method that is commonly used is passing cooling fluid through the stator laminations or into slots cut into the stator laminations. Either of these has similar but not as severe disadvantages to the cooling jacket design. Additionally, it typically requires the stator to get larger to accommodate the holes in the magnetic material.

Further, some techniques involve spraying fluid directly on the stator or submerging the stator. These have the disadvantage of either being overly complex or having the fluid cause drag between the rotor and the stator.

There are at least two techniques placing the cooling manifold through the winding slot. One of these is forcing fluid down the center of a conductor. Typically the fluid in this case is a non-conductive oil. This has the disadvantage of requiring a special fluid and some complex manufacturing methods to provide the fluid channel. For extremely high powers in the 10MW and above range the cooling media is often hydrogen. Other techniques place a pipe or vessel down through the slot with cooling fluid in it. These typically also use non-conductive oil and have non-conductive connections to a manifold at their end. An example of this can be found in U.S. patent # 3,112,415 entitled CONTROL OF WINDING TEMPERATURES OF LIQUID COOLED GENERATORS, incorporated herein by reference.

This design integrates the cooling manifold into the stator slot directly adjacent to the wires that generate the heat. This accommodates use of standard ethylene glycol coolant which is highly desired in the industry, and achieves very compact machines.

Novel methods of cooling by the same inventor are also shown in other applications filed by Marvin et al U.S. patent application serial number 13548199 entitled LIQUID COOLED HIGH EFFICIENCY PERMANENT MAGNET MACHINE WITH GLYCOL COOLING, serial number 13548203 entitled LIQUID COOLED HIGH EFFICIENCY PERMANENT MAGNET MACHINE WITH IN SLOT GLYCOL COOLING, serial number 13548207 entitled HIGH EFFICIENCY PERMANENT MAGNET MACHINE WITH CONCENTRATED WINDING AND DOUBLE COILS, and serial number 13548208 entitled HIGH EFFICIENCY PERMANENT MAGNET MACHINE WITH LAYER FORM WINDING all filed July 13, 2012, all incorporated herein by reference.

The most common stator winding type is a distributed winding. One type of which is an integer-slot winding wherein the number of slots per pole per phase is an integer. An example of this is a 4 pole 12 slot, 3 phase motor. The number of slots per pole per phase is 1 and therefore an integer. These windings typically require some relatively complex end turns to wire them properly. One type of construction is a

diamond form winding that is used in many of the larger, higher voltage, and more reliable machines.

Another type of winding is a concentrated winding when the number of slots per pole per phase is a fraction less than one. These can also be called a non-overlapping concentrated winding. They have the disadvantage of decreasing the inherent efficiency of the device, but make the end turns very simple and can facilitate other advantages. An example of a concentrated winding would be an 8 pole, 9 slot, 3 phase machine. The number of slots per pole per phase is 0.375 in this case. The fundamental power from this configuration is reduced by 5.5%. Concentrated windings can be single layer or double layer designs. Single layer designs have windings that are wound only on alternating stator teeth and only apply where there is an even number of stator slots/teeth. Double layer designs have coils wound on every stator tooth. In this configuration, there is a coil that surrounds each of the teeth on the stator and there are the same number of coils as slots. Further, each slot has half of one coil and half of another coil going through the slot and the end turns are very short. Ideally, the end turns can be as short as the width of the stator tooth.

Double layer concentrated windings have the advantage of being a simple coil wrapped around each tooth. For an external rotor configuration, and using relatively open slots, this allows simple assembly of coils. For the more typical internal rotor configuration, assembly is a bit trickier because even with relatively open slots, the opening is smaller than the slot. This is further complicated if the slot opening is made smaller for motor performance reasons. A typical method of mitigating this issue is to make the teeth separate to either be able to 1) wind the wire directly on the tooth or 2) slide the winding on from the outside. The first method is shown in U.S. patent 5,583,387 entitled STATOR OF DYNAMO-ELECTRIC MACHINE incorporated herein by reference. The second method is shown in U.S. patent 4,712,035 entitled SALIENT POLE CORE AND SALIENT POLE ELECTRONICALLY COMMUTATED MOTOR also incorporated herein by reference although it is shown as an external rotor configuration. Both methods are shown as conventional in U.S. patent 8,129,880 entitled CONCENTRATED WINDING MACHINE WITH MAGNETIC SLOT WEDGES, incorporated herein by reference. The challenge with any stator lamination design that has separate teeth is to secure the teeth structurally so

they do not move or break. Even small movements of the teeth can cause acoustic noise. A second challenge is to configure the joint in such a way to not significantly disturb the magnetic flux traveling through the laminations. If the joint could be made with zero clearance this would not be a problem, but with real manufacturing tolerances and features required for attachment, this is a major consideration.

Rotary electric machines including electric motors, generators, and the like have employed various methods of constructing stator windings. Some methods are applicable to only certain types of stator windings.

One common method is random winding. This method can use rectangular or round wire, but typically uses round wire. Here the windings are placed by the winding machine with the only requirement that they be located in the correct slot. This is the easiest method of stator winding, but results in the lowest amount of conductor in the slot and therefore the lowest efficiency. This method can be used with any type of stator winding including concentrated windings.

Another common method is diamond form winding. This method typically uses rectangular wire with various tapes located between conductors to separate any conductors that are significantly different in voltage and the shape of the coil is in a diamond shape. This is a robust winding for higher voltage machines or machines that are prone to partial discharge. This is typically the most labor-intensive type of winding due to the manufacture of the coils and the insertion time to put these coils in the machine from the inside. This labor time can be improved by insertion from the outside which is one of the objects of the design disclosed in this patent.

One winding type that is not typical in motors, is used in certain types of transformers, chokes, and inductors is bobbin layer winding. This type of winding places conductors in exact locations for very accurate stacking of wires. This can achieve a high amount of conductors in a small area for high efficiency. This is not typically used for distributed windings because you are not able to bobbin wind a coil and then insert it into a stator assembly. This is possible with concentrated windings that have removable teeth. The most common wire to use is round wire but it is possible to use square or rectangular wire. Layer winding with rectangular wire is typically laid flat and wound the easy way. This facilitates simpler winding, but one disadvantage of this is the eddy current losses due to slot leakage can be significantly

higher. Also, orientation of the rectangular wire can have an impact on thermal performance and depends on the overall heat removal scheme.

Layer winding with rectangular wire can be done edge wound (wound the hard way.) This is shown in U.S. patent 4,446,393 entitled DYNAMOELECTRIC FIELD ASSEMBLY AND WINDING THEREFOR incorporated herein by reference. In this patent a single layer of rectangular wire is used in each slot and is edge wound. This patent used removable teeth and an internal rotor. U.S. patent application serial number 2010/0066198 filed March 18, 2010 entitled INSERTION OF PRE-FABRICATED CONCENTRATED WINDINGS INTO STATOR SLOTS incorporated herein by reference also shows a single layer of rectangular wire but does not use removable teeth. Edge wound coils can have significantly lower eddy current losses in the wires. The cooling may be better or worse depending on the overall cooling scheme.

Summary of the Invention

The machine described herein incorporates several novel construction methods in its stator. The key is different approaches to accommodate liquid cooling in the slot in an economical efficient approach.

The preferred design uses either Edge Form Wound Windings for concentrated wound machines or Diamond Form Wound Windings for distributed wound machines. The preferred approach places the cooling manifold in the center of the slot between two sets of windings. In certain applications it makes sense to put at least some of the cooling manifold in different locations in the slot. This general approach insures a very good thermal solution that allows much higher current density in the slot. Higher current density in the slot allows significantly higher overall torque density of the rotating machine. The machine described herein also allows the use of conductive fluid such as ethylene glycol.

This configuration uses metallic vessels that contain the liquid cooling medium for high reliability. These metallic vessels are brazed together into manifolds to efficiently direct the liquid to where the heat is generated. The specific geometry and connectivity of the cooling manifolds allows this to be done without detrimental effects to the performance of the machine.

The overall approach leads to a very reliable, compact, efficient, and low cost design.

In accordance with one example embodiment of the present invention, a rotary electric machine is disclosed that comprises a stator having a circumaxially spaced series of axially extending teeth defining a similar series of circumaxially spaced winding slots there between. A plurality of stator windings are at least partially disposed respectively in the slots, the windings being electrically connected to form a plurality of phases wherein one or more slots contain the same magnitude of current at substantially all times for each phase. A means is provided that defines a plurality of elongated coolant passageways disposed respectively in the slots; wherein a subset of coolant passageways contained in the slots for a single phase is an even number and fluid flows in one direction for half of this subset of coolant passageways and in the opposite direction for the other half of this subset of coolant passageways. At least two of the coolant passageways in the whole machine are connected fluidically in parallel; and at least one of the coolant passageway is located circumaxially between two windings.

The illustrated rotary electric machine has coolant passages that are constructed of an electrically conductive material. In one example, the coolant is a liquid. In one disclosed embodiment, the coolant passageways are attached using a brazed connection and the slots each have the same number of coolant passageways going in one direction as are going in an opposite direction. In one preferred arrangement of an illustrated embodiment, the coolant passageway is located circumaxially between winding and tooth (of this illustrated embodiment). According to a feature of one of the embodiments, there is included a compliant insulating layer located between winding and coolant passageways. In one preferred embodiment example, the machine is a distributed wound machine. In another embodiment, the machine is a concentrated wound machine.

In another embodiment example, at least some of the coolant passageways are formed by a plurality of generally adjacent structures that are fluidically connected at only one end of the machine.

According to one exemplified embodiment, a method is disclosed for building stator assemblies that contain in-slot cooling manifolds and separable teeth. According to the method, in a first step the teeth comprise an assembly of stator teeth, in-slot cooling manifolds and windings first, then followed by a step of insertion of an outer

yolk assembly in an axial direction, then followed by a step of securing of the standard teeth.

Additional features of the invention will become apparent and a fuller understanding will be obtained by reading the following detailed description accompanied by the attached drawings.

Brief Description of the Drawings

Fig. 1 is a three dimensional view of the stator assembly for a distributed wound machine,

Figure 2 is a side view of the stator assembly of Figure 1,

Figure 3 is a sectional view of the stator assembly shown in Figure 1 and Figure 2,

Figure 4 is an enlarged detail sectional view of the stator assembly shown in Figure 3,

Figure 5 is a three dimensional view of the stator assembly for a concentrated wound machine,

Figure 6 is a cross sectional view of the stator assembly shown in Figure 5,

Figure 7 is an enlarged detail sectional view of the stator assembly shown in Figure 6,

Figure 8 is a three dimensional view of a diamond coil,

Figure 9 is a fluid schematic of the cooling system.

Detailed Description of Preferred Embodiment

Referring particularly to Figure 1, a distributed wound stator assembly is shown containing stator yoke 1, stator coil 2, stator coil 3, and stator lamination teeth 4. There are two different stator coils 2,3 shown due to the fact that they are not evenly spaced and therefore are of slightly different shape. In order to accommodate assembly of the machine the coils 2,3 are bent inward on at least one end as shown in Figure 2 where coil ends 2a,3a are bent inward and coil ends 2b,3b are bent in a more conventional configuration. The joint between the stator teeth 4 and stator yoke 1 can be seen clearly in Figure 3.

In the cross section view of Figure 4, the coil bundles can be seen as 5,6,7, and 8. Each of these coil bundles can be made up of anywhere from a single turn to many turns. The wire is rectangular in shape with the wide dimension on the wire being in

the circumaxial direction of the machine. This is the same direction as the narrow dimension on the coil bundle as shown in Figure 4. This can be accomplished by forming the coils in a diamond shape as shown in Figure 8. This diamond shape coil has straight sections 38, pin turns 39a and 39b, bends in the easy way 40 and bends in the hard way 41.

As shown in Figure 4, the cooling manifold in each slot consist of 4 cooling bars 9,10,11, and 12 which are manufactured by aluminum extrusion and therefore electrically conductive. Aluminum is used for ease of manufacturing and the attachment to the slot manifold can be done using a brazing process. Preferably cooling goes down in one slot and up in the other slot in that same cooling bar. The cooling bars are separated by insulator 13, 14, and 15 made of a solid insulator such as PPS. There is also a slot liner 19 that wraps the entire way around the slot with overlap that is made of Nomex or similar. Located between cooling bars 9,10,11,12 and coil bundles 5,6 is an insulator 17 that is preferably a thermally conductive electrically insulative material. Further, this material preferably is made of a compressible material to accomplish good thermal contact between the cooling bars and the coil bundles. One material that fits this need is filled Silicon rubber gap filler pads sold by Parker Chomerics and others. If additional compliance is needed to absorb tolerance, a compressible pad 18 can be placed between coil bundles 5,6 and slot liner 19 or alternatively between slot liner 19 and tooth 4.

To accommodate the tooth tips 23a, 23b being located close together and to accommodate the easy insertion of coils, the stator teeth 4 are made a separate part from stator yoke 1 so the coils and cooling manifold can be assembled from the outside diameter. The tooth attachment scheme shown consists of a narrow cantilever beam located on the tooth that is pulled radially outward using wedges 22a and 22b that are electrically insulated from the stator by insulator 21.

It is unusual for a distributed wound stator assembly to have separable teeth. Typically windings are inserted from the inside through wide tooth tip gaps. The preferred assembly approach for this distributed wound stator is to place the teeth 4, windings 4,5,6,7, cooling manifolds 9,10,11,12, and various insulators 17,18,19 into an assembly fixture. This assembly would take place at a slightly larger diameter than final size to accommodate tolerances and assembly clearances. The fixture would then

draw down the diameter to slightly smaller than the final diameter compressing the compressible members 17,18 in the slot. The stator yoke 1 is then inserted axially over the assembly. The fixture then allows the diameter to increase outwardly expanding the compressible members 17,18 in the slot. Now the wedges 22 and associated insulator 21 can be installed to draw the teeth 4 into final position. The assembly is now ready for vacuum pressure impregnation (VPI) with an epoxy resin.

Figure 9 shows a fluid schematic for a 6 slot 3 phase machine where slot manifold A is located in phase A, slot manifold B is located in phase B, and slot manifold C is located in phase C. Each phase constitutes windings that all have the same current in each one. Multiple winding can be connected in series or parallel and still have substantially the same current in each one. In a three phase machine, phases are typically connected in either a wye or delta configuration which does not affect the design.

As shown in Figure 9, there are two cooling bars for each slot each with its own turnaround. The diagram also shows the two cooling bars in each slot fluidically in series, but alternately they could be connected in parallel or partially parallel and series. This diagram shows each of the slot manifolds fluidically in parallel, but alternately they could be connected in series or partially parallel and series. The schematic for stator in Figure 3 would look much the same except there would be 12 slots and 4 cooling bars for each slot. Figure 9 shows all fluid interconnections at one end. Alternately, some of the fluid connections can be made on the opposite end, but the number of passages flowing up in each phase must equal the number of passages flowing down in each phase. The media flowing in each of the coolant loops is preferably a 50% mixture of ethylene glycol and water so the liquid will not freeze at cold temperatures.

An alternate configuration in Figure 5 is shown as a three dimensional view of a concentrated wound stator. The stator yoke 24, stator teeth 25, and windings 26 accomplish this concentrated wound configuration. Figure 6 shows a cross sectional view that better shows the stator yoke 24 and stator teeth 25. The cross sectional view of the windings is better shown in Figure 7 where coil bundles 28,19,30, 31 are shown that comprise a single winding. This configuration shows cooling bars 32 and 33 located in the middle of the slot between windings as well as cooling bars 34,35,36, 37

located between the tooth 25 and the windings. Alternate configurations could have only some of these cooling bars, have fewer or more coil bundles in each winding, or be a distributed wound solution. The wire is rectangular in shape with the wide dimension on the wire being in the circumaxial direction of the machine. This is the same direction as the narrow dimension on the coil bundle as shown in Figure 7.

Although the invention has been described with a certain degree of particularity, it should be understood that those skilled in the art can make various changes to it without departing from the spirit or scope as hereinafter claimed.

Having described the invention, the following is claimed:

1. A rotary electric machine comprising a stator having a circumaxially spaced series of axially extending teeth defining a similar series of circumaxially spaced winding slots therebetween, a plurality of stator windings at least partially disposed respectively in the slots, said windings being electrically connected to form a plurality of phases wherein one or more slots contain the same magnitude of current at substantially all times for each phase; means defining a plurality of elongated coolant passageways disposed respectively in the slots; wherein a subset of coolant passageways contained in the slots for a single phase is an even number and fluid flows in one direction for half of this subset of coolant passageways and in the opposite direction for the other half of this subset of coolant passageways; wherein at least two of the coolant passageways in the whole machine are connected fluidically in parallel; and at least one of said coolant passageway is located circumaxially between two windings.
2. A rotary electric machine as set forth in claim 1 wherein said coolant passageways are constructed of an electrically conductive material.
3. A rotary electric machine as set forth in claim 1 wherein said coolant is a liquid.
4. A rotary electric machine as set forth in claim 1 wherein said coolant passageways are attached using a brazed connection.
5. A rotary electric machine as set forth in claim 1 wherein said slots each have the same number of coolant passageways going in one direction as are going in the opposite direction.
6. A rotary electric machine as set forth in claim 1 wherein at least one of said coolant passageway is located circumaxially between winding and tooth.

7. A rotary electric machine as set forth in claim 1 wherein there is a compliant insulating layer located between winding and coolant passageway.
8. A rotary electric machine as set forth in claim 1 wherein the machine is a distributed wound machine.
9. A rotary electric machine as set forth in claim 1 wherein the machine is a concentrated wound machine.
10. A rotary electric machine comprising a stator having a circumaxially spaced series of axially extending teeth defining a similar series of circumaxially spaced winding slots therebetween, a plurality of stator windings at least partially disposed respectively in the slots, said windings being electrically connected to form a plurality of phases wherein one or more slots contain the same magnitude of current at substantially all times for each phase; means defining a plurality of elongated coolant passageways disposed respectively in the slots; wherein a subset of coolant passageways contained in the slots for a single phase is an even number and fluid flows in one direction for half of this subset of coolant passageways and in the opposite direction for the other half of this subset of coolant passageways; wherein at least two of the coolant passageways in the whole machine are connected fluidically in parallel; and at least some of said coolant passageways are formed by a plurality of generally adjacent structures that are fluidically connected at only one end of the machine.
11. A rotary electric machine as set forth in claim 10 wherein at least one of said coolant passageway is located circumaxially between two windings.
12. A rotary electric machine as set forth in claim 10 wherein said coolant passageways are constructed of an electrically conductive material.
13. A rotary electric machine as set forth in claim 10 wherein said coolant is a liquid.

14. A rotary electric machine as set forth in claim 10 wherein said coolant passageways are attached using a brazed connection

15. A rotary electric machine as set forth in claim 10 wherein said slots each have the same number of coolant passageways going in one direction as are going in the opposite direction.

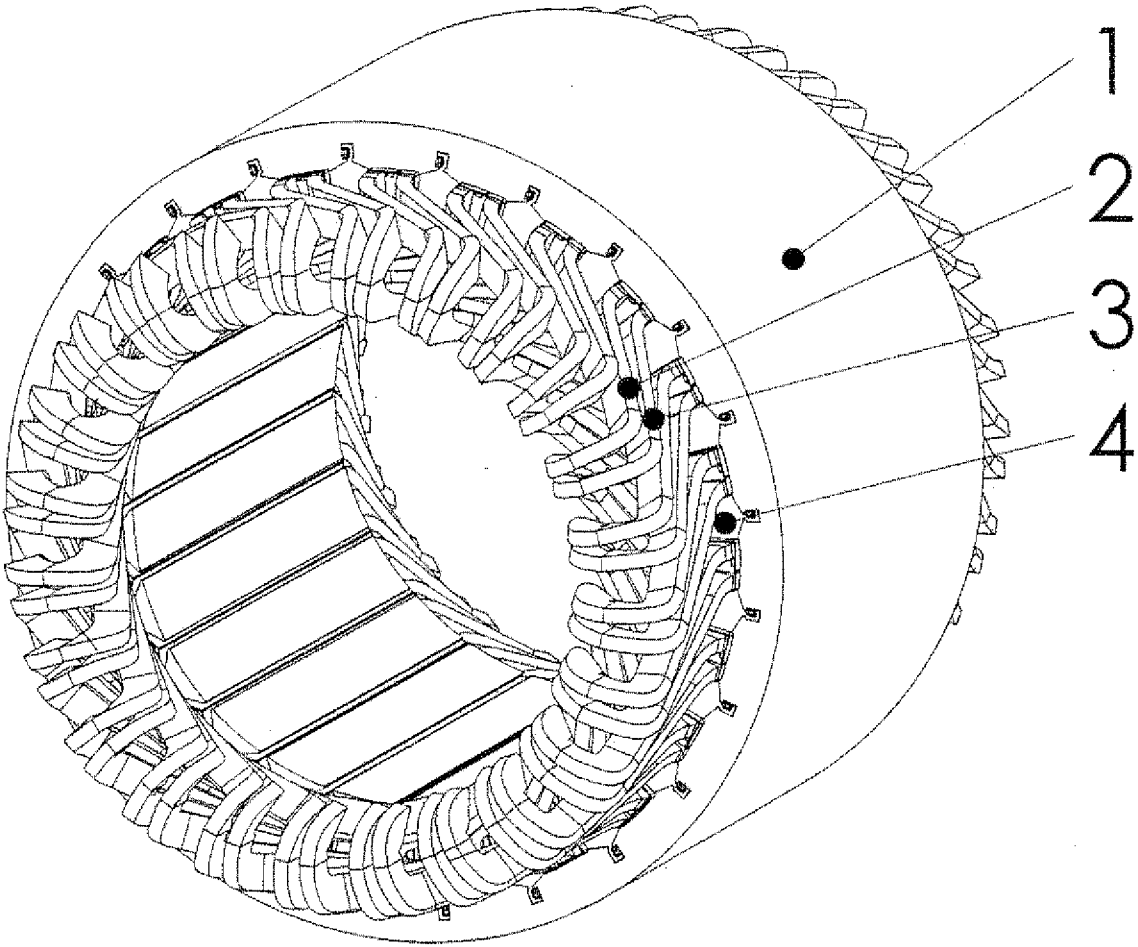
16. A rotary electric machine as set forth in claim 10 wherein at least one of said coolant passageway is located circumaxially between winding and tooth.

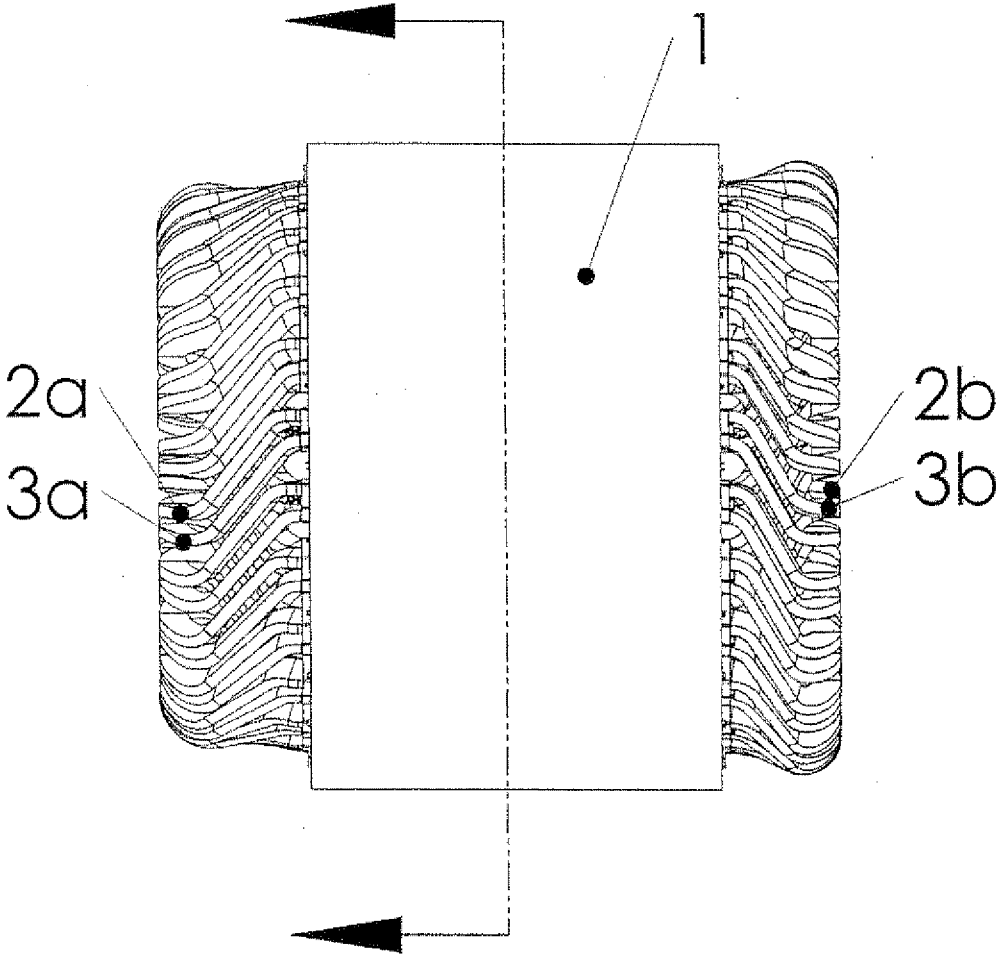
17. A rotary electric machine as set forth in claim 10 wherein there is a compliant insulating layer located between winding and coolant passageway.

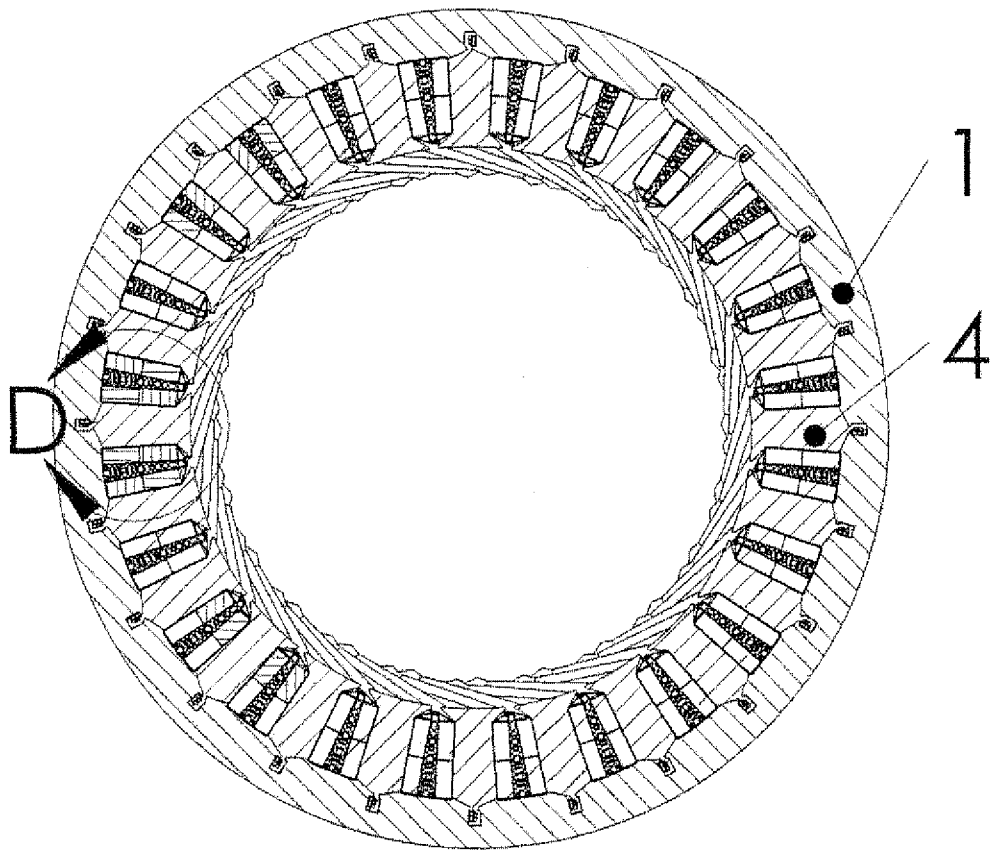
18. A rotary electric machine as set forth in claim 10 wherein the machine is a distributed wound machine.

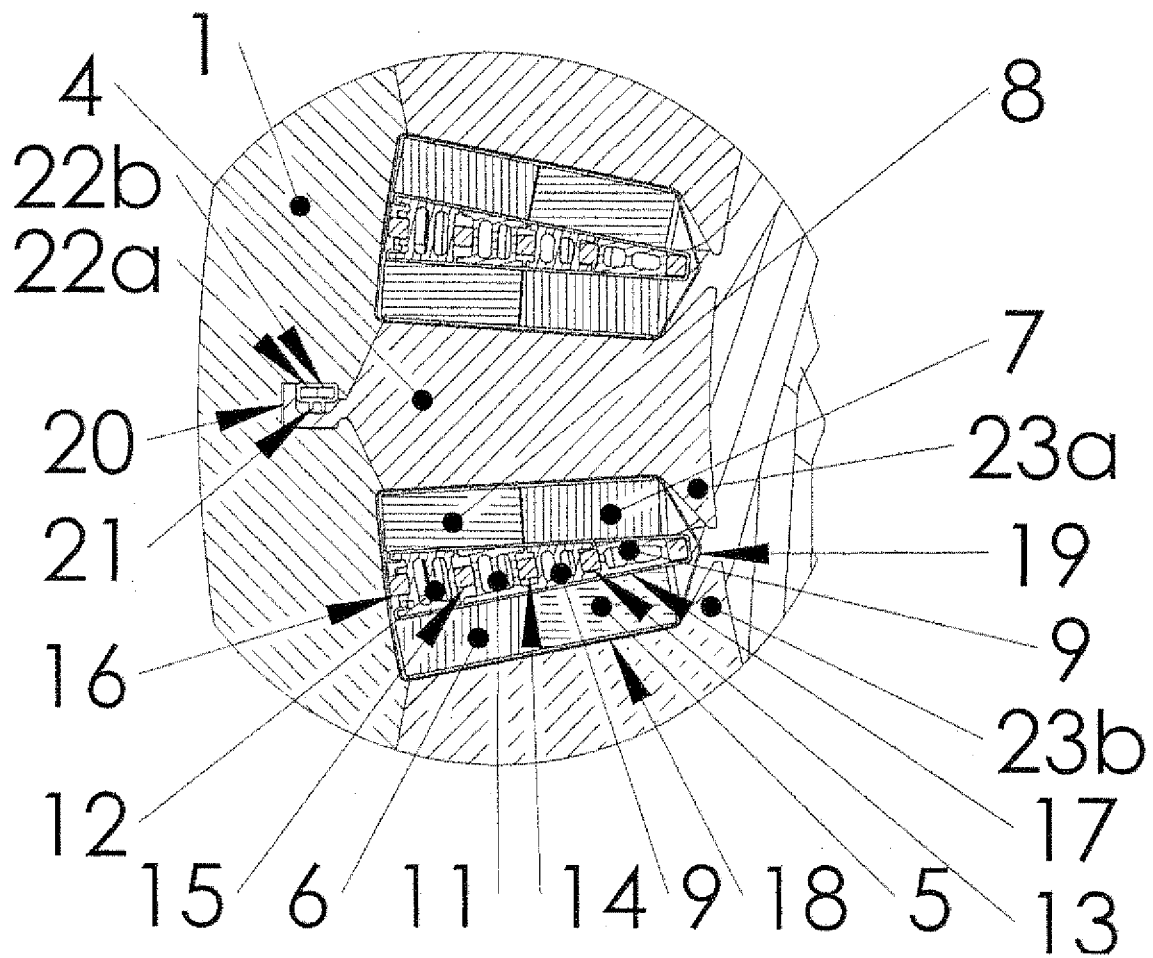
19. A rotary electric machine as set forth in claim 10 wherein the machine is a concentrated wound machine.

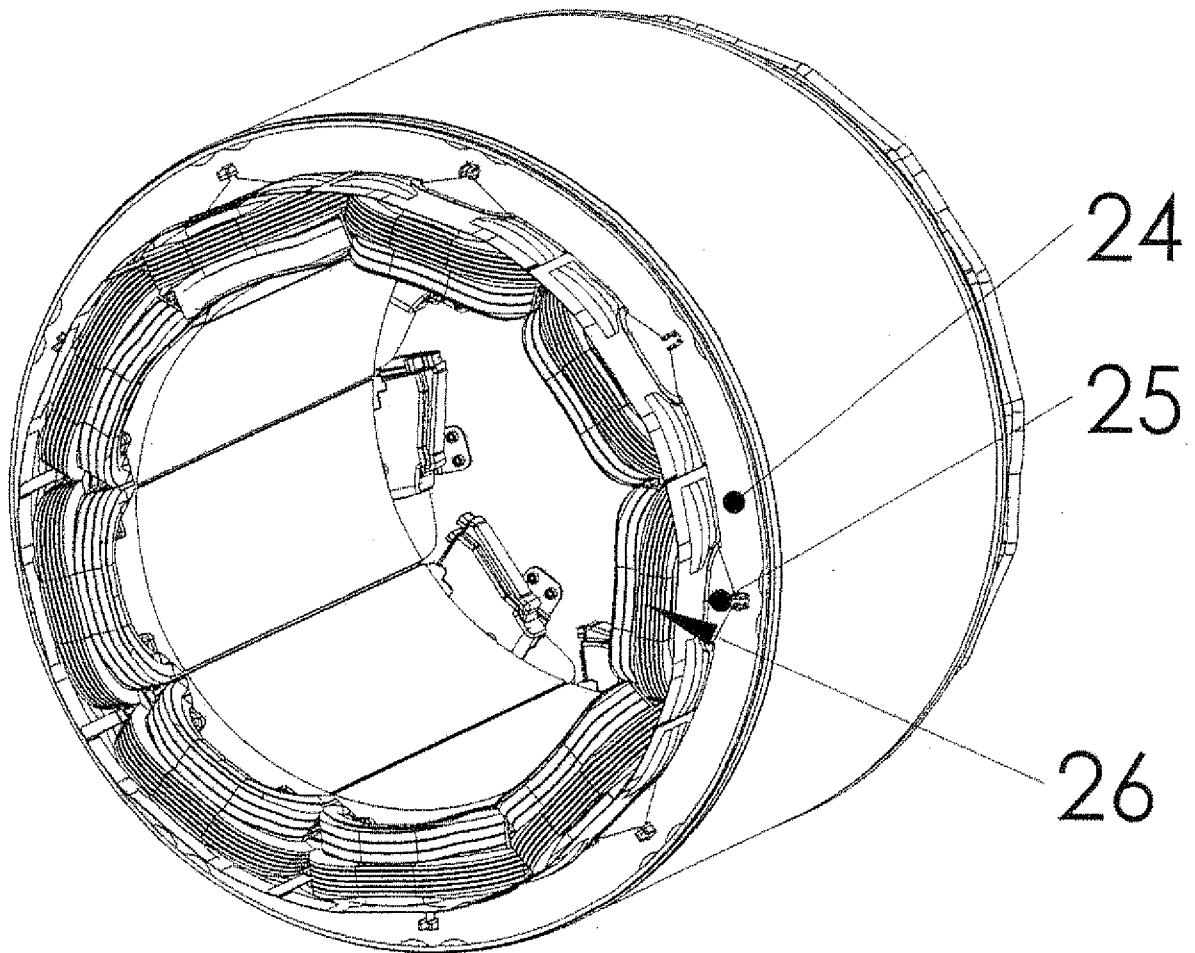
20. A method for building stator assemblies that contain in-slot cooling manifolds and separable teeth consisting of assembly of the stator teeth, in-slot cooling manifolds, and windings first, then followed by insertion of outer yoke assembly in an axial direction, then followed by securing of the stator teeth.

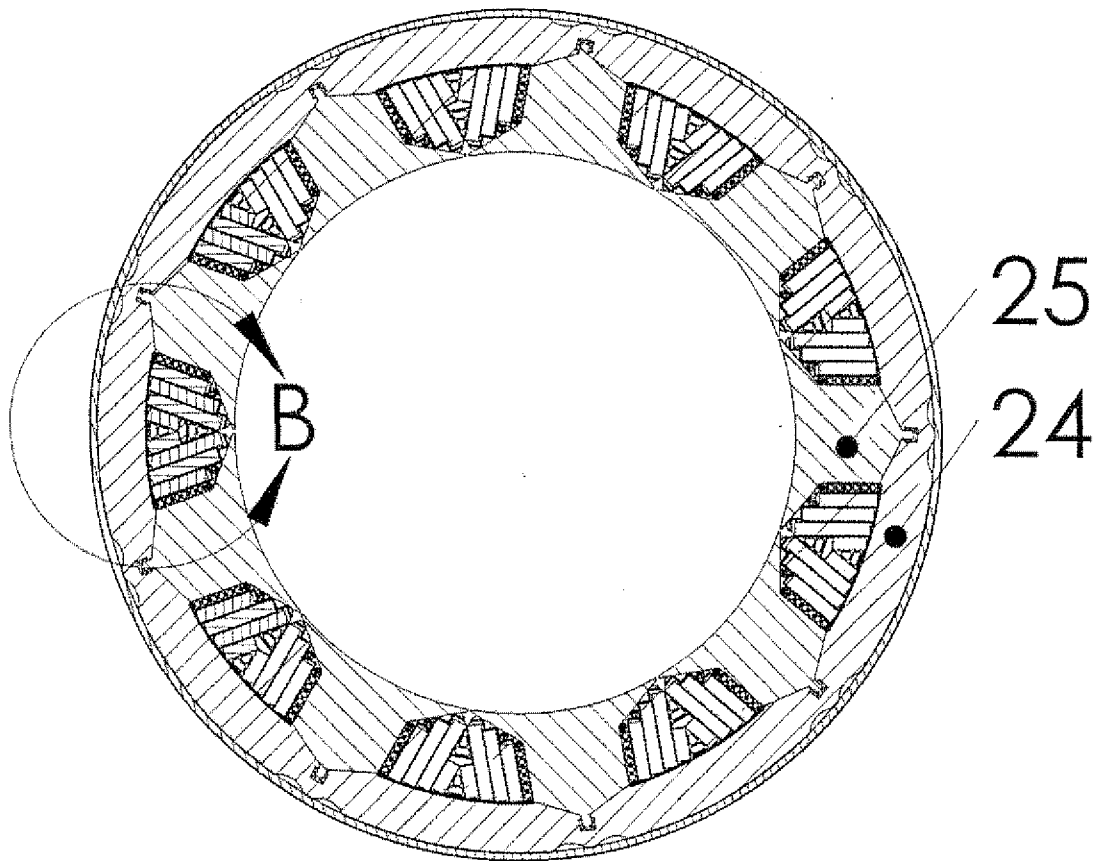


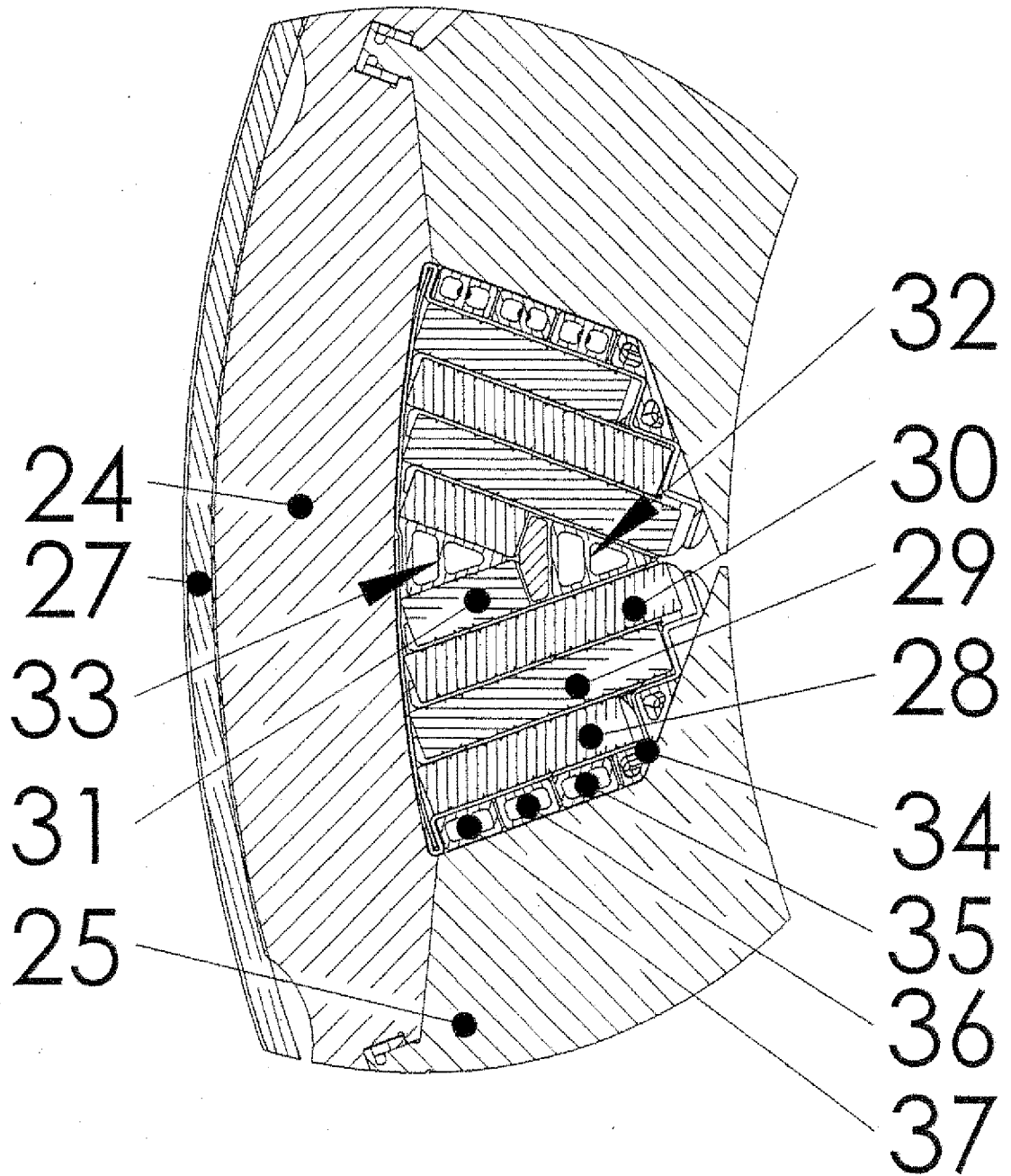


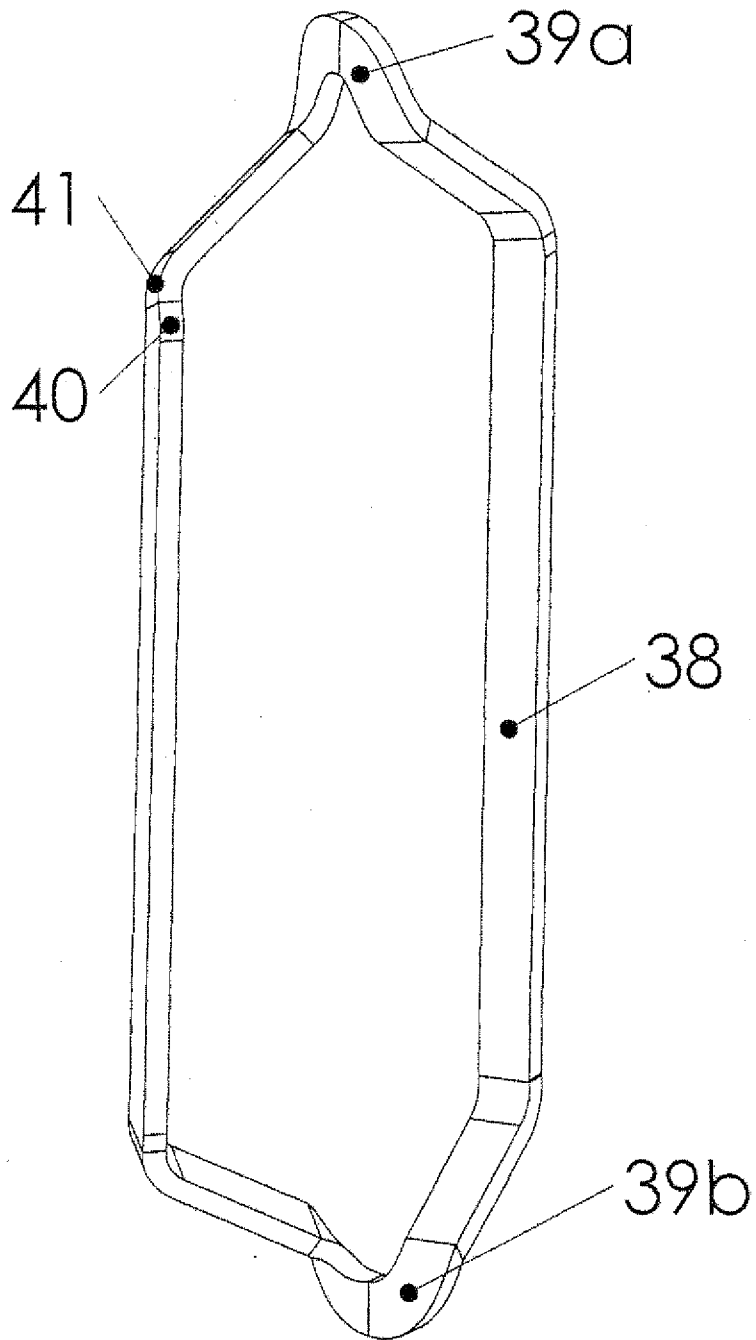


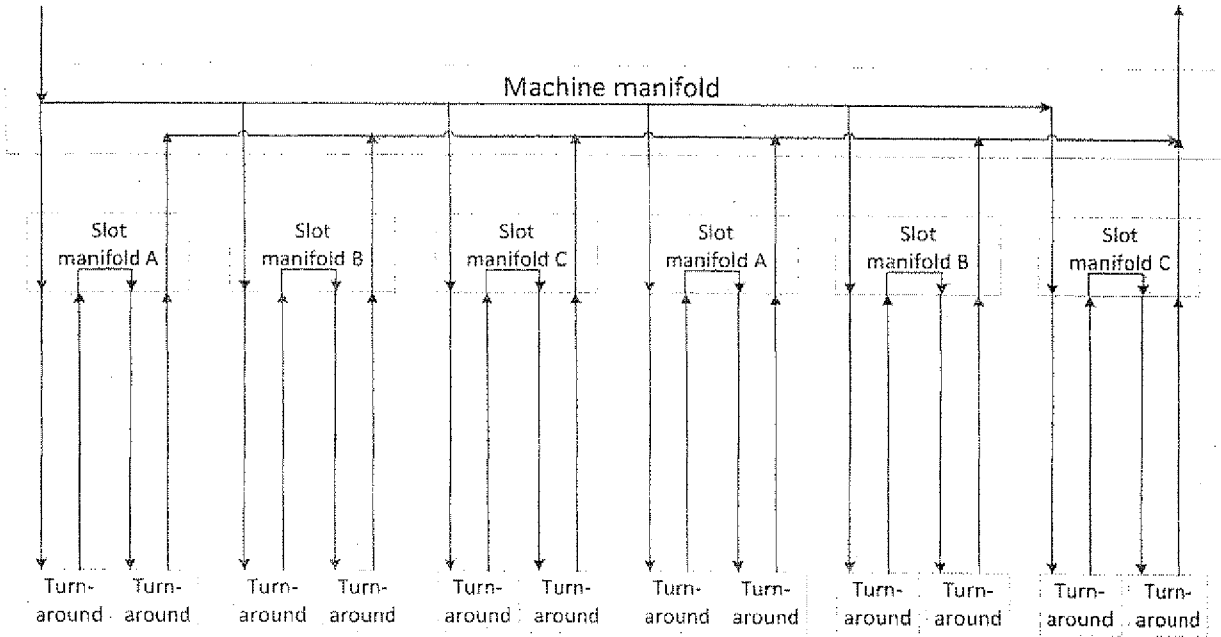












INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2014/032369

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H02K 3/24 (2014.01)

USPC - 310/52

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)

IPC(8) - G01K 3/02; G08B 17/00; H02K 3/24 (2014.01)

USPC - 310/52, 53, 54, 58, 59, 64; 340/584, 679; 364/557

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

CPC - G01K 3/02; G08B 17/00; H02K 3/24 (2014.07)

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

PatBase, Google Patents, Google, YouTube

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,973,427 A (SUZUKI et al) 26 October 1999 (26.10.1999) entire document	1-20
Y	US 2011/0133580 A1 (SUGIMOTO et al) 09 June 2011 (09.06.2011) entire document	1-19
Y	US 2007/0278879 A1 (KAMINSKI et al) 06 December 2007 (06.12.2007) entire document	4, 14
Y	US 2002/0117936 A1 (DRESSEL) 29 August 2002 (29.08.2002) entire document	20

☐ Further documents are listed in the continuation of Box C.

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Date of the actual completion of the international search

21 July 2014

Date of mailing of the international search report

13 AUG 2014

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