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(54) DIRECT LIQUID COOLING SYSTEMS AND METHODS FOR MAGNETS OF INTERIOR PERMANENT MAGNET ELECTRIC MACHINES

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H02K 21/14	(2006.01)

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(58) **Field of Classification Search**

CPC H02K 1/32; H02K 9/19

USPC 310/54

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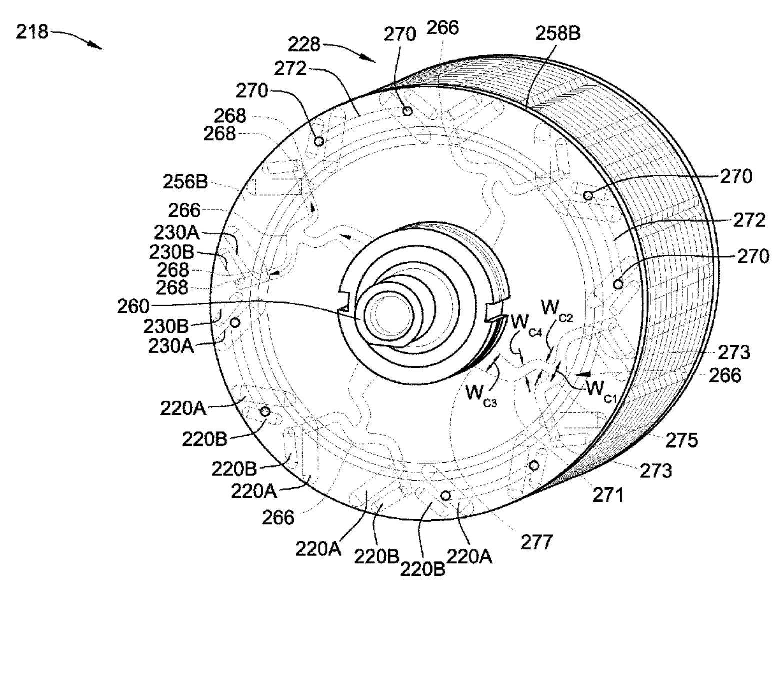
(57) **ABSTRACT**

Presented are direct liquid cooling systems for regulating magnet temperature of electric machines, methods for making/using such systems, and motor vehicles equipped with traction motors having magnets cooled by such systems. An electric machine includes a stator assembly that is located inside a protective outer housing. The stator assembly includes one or more electromagnetic windings mounted onto a stator core. A rotor assembly is rotatably attached to the housing, coaxial with and spaced from the stator assembly. The rotor assembly includes one or more permanent magnets mounted to a rotor core. The rotor core includes one or more radially elongated feed grooves that are fluidly connected to one or more axially elongated feed channels. The rotor feed groove(s) fluidly connect to a direct liquid cooling system to receive therefrom a liquid coolant. Each rotor feed channel transports the liquid coolant into direct contact with a target surface of a magnet.

20 Claims, 4 Drawing Sheets



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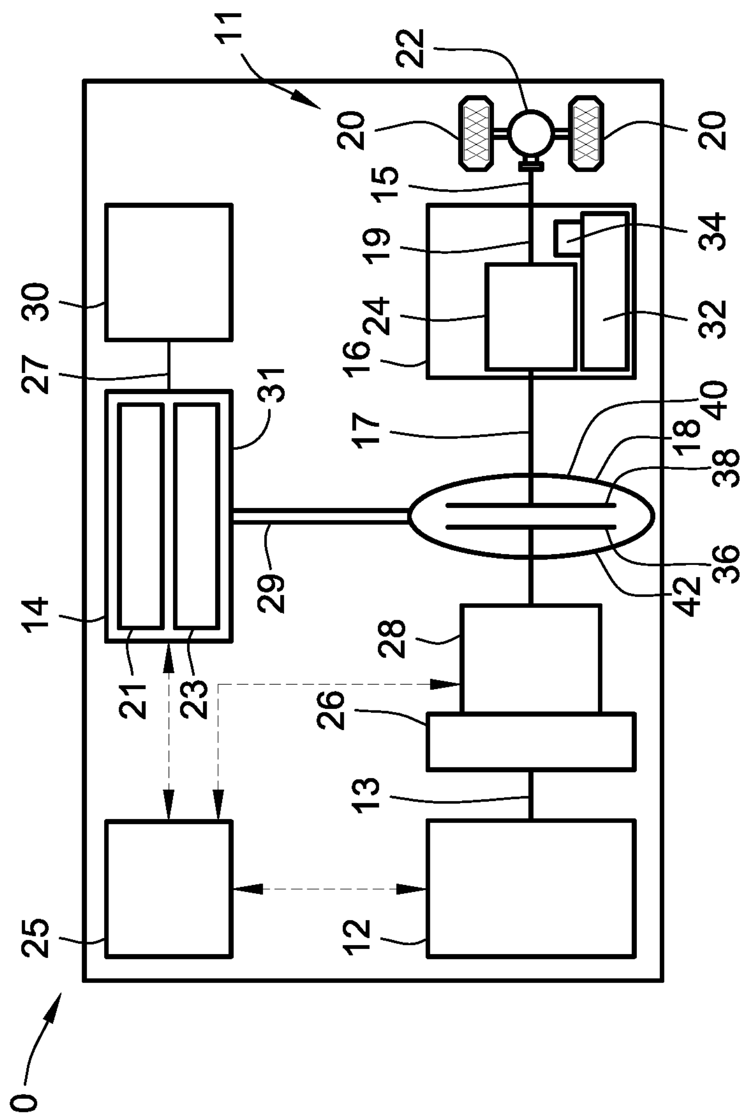
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FIG. 1

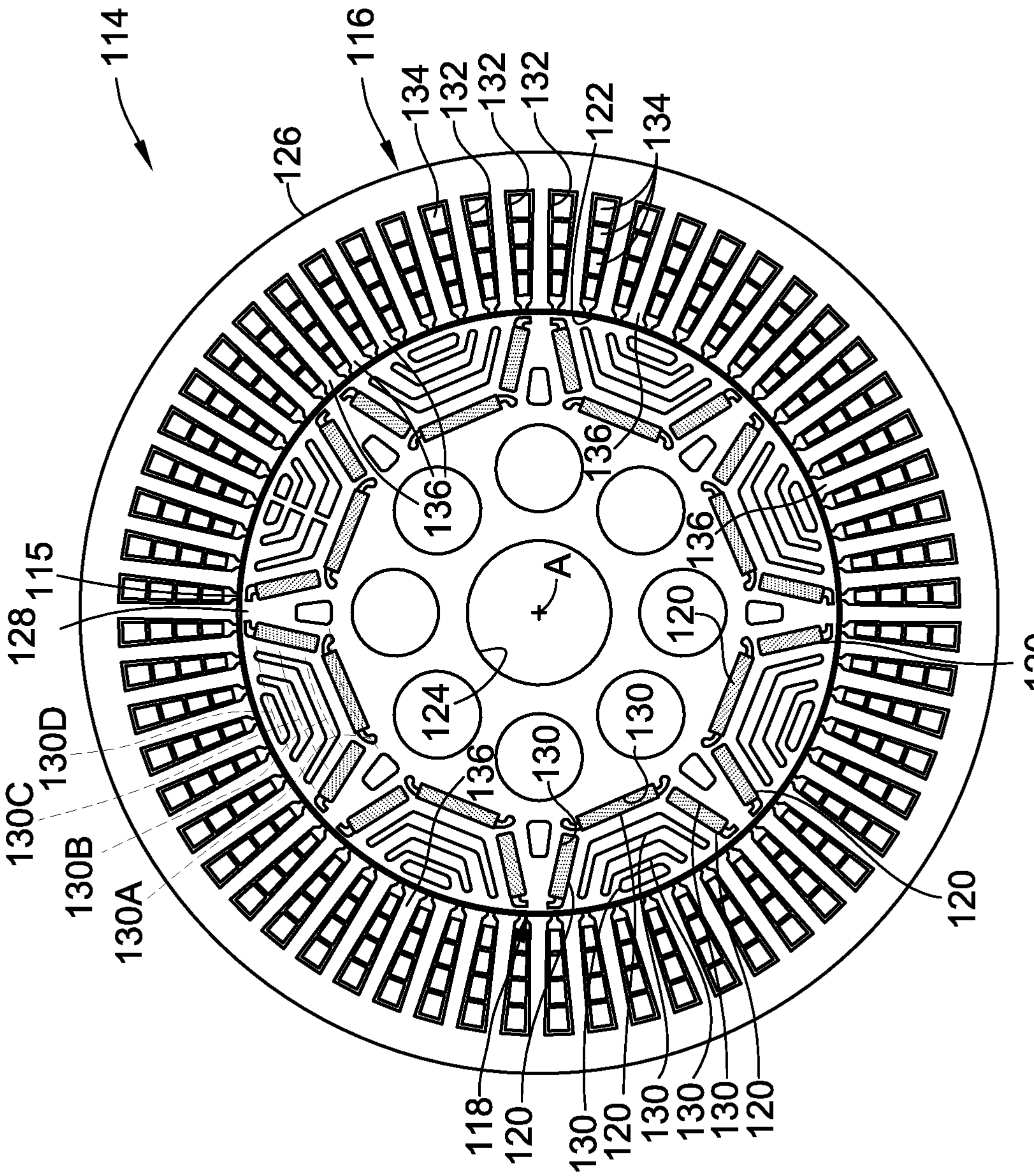
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FIG. 2

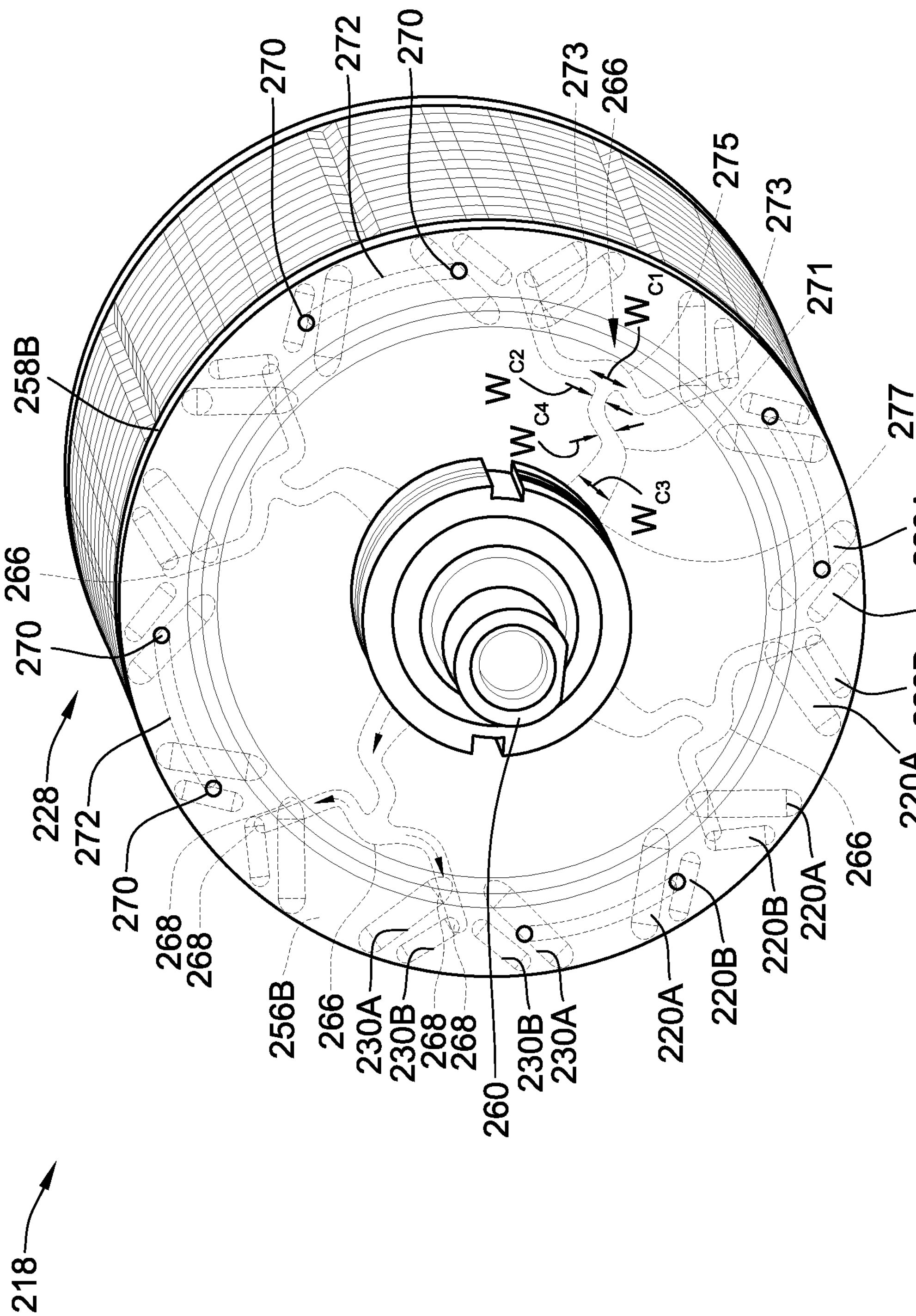
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FIG. 3

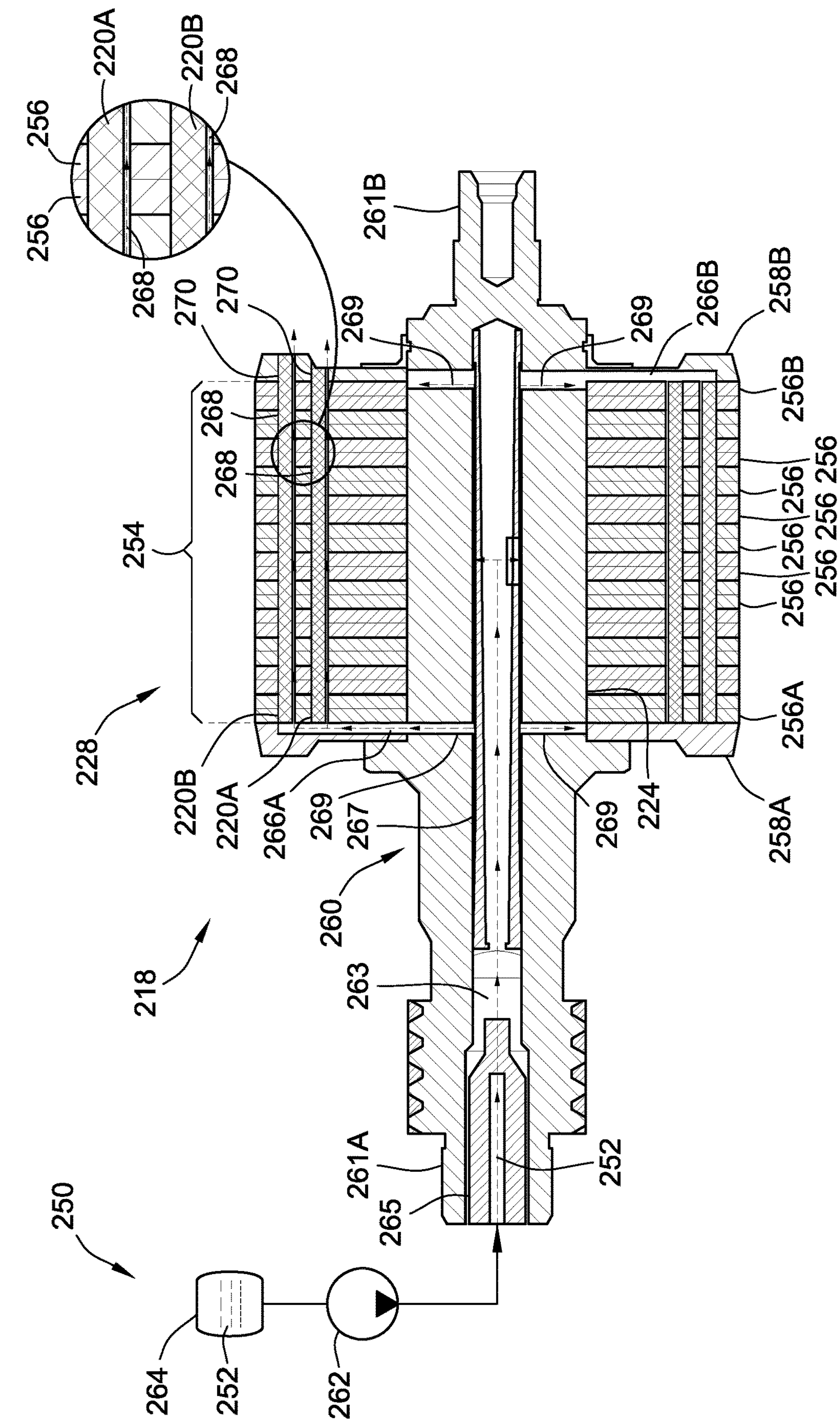
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FIG. 4

DIRECT LIQUID COOLING SYSTEMS AND METHODS FOR MAGNETS OF INTERIOR PERMANENT MAGNET ELECTRIC MACHINES

INTRODUCTION

The present disclosure relates generally to electric machines. More specifically, aspects of this disclosure relate to direct liquid cooling systems for interior permanent magnet (IPM) electric motors.

Current production motor vehicles, such as the modern-day automobile, are originally equipped with a powertrain that operates to propel the vehicle and power the vehicle's onboard electronics. In automotive applications, for example, the vehicle powertrain is generally typified by a prime mover that delivers driving torque through an automatic or manually shifted power transmission to the vehicle's final drive system (e.g., differential, axle shafts, corner modules, road wheels, etc.). Automobiles have historically been powered by a reciprocating-piston type internal combustion engine (ICE) assembly due to its ready availability and being relatively inexpensive, light weight, and overall efficient. Such engines include compression-ignited (CI) diesel engines, spark-ignited (SI) gasoline engines, two, four, and six-stroke architectures, and rotary engines, as some non-limiting examples. Hybrid-electric and full-electric vehicles (collectively "electric-drive vehicles"), on the other hand, utilize alternative power sources to propel the vehicle and, thus, minimize or eliminate reliance on a fossil-fuel based engine for tractive power.

A full-electric vehicle (FEV)—colloquially labeled an "electric car"—is a type of electric-drive vehicle configuration that altogether omits an internal combustion engine and attendant peripheral components from the powertrain system, relying instead on a rechargeable energy storage system (RESS) and a traction motor for vehicle propulsion. The engine assembly, fuel supply system, and exhaust system of an ICE-based vehicle are replaced with a single or multiple traction motors, rechargeable battery cells, and battery cooling and charging hardware in a battery-based FEV. Hybrid-electric vehicle (HEV) powertrains, in contrast, employ multiple sources of tractive power to propel the vehicle, most commonly operating an internal combustion engine assembly in conjunction with a battery-powered or fuel-cell-powered traction motor. Since hybrid-type, electric-drive vehicles are able to derive their power from sources other than the engine, HEV engines may be turned off, in whole or in part, while the vehicle is propelled by the electric motor(s).

There are three primary types of electric machines used for traction motors in modern electric-drive vehicle powertrains: brushless direct current (BLDC) permanent magnet (PM) motors, brushless asynchronous alternating current (AC) motors, and multiphase synchronous ACPM motors. An ACPM traction motor is an electric machine that converts electrical energy into rotational mechanical energy using a stator with multiphase electromagnetic windings, such as electrically conductive "hairpin" bars, and a rotatable rotor that bears an engineered pattern of magnets, such as surface-mounted or interior-mounted permanent magnets. Rotation of the rotor is effected by a magnetic field that is produced by the flow of current through the stator windings and interacts with a magnetic field produced by the rotor-borne magnets. Permanent magnet motors have a number of operating characteristics that make them more attractive for use in vehicle propulsion applications when compared to

their available counterparts, including high efficiency, high torque, high power densities, and a long constant-power operating range.

The rotor assemblies for many modern-day ACPM motors are fabricated with a rotor core that is formed from thin ferromagnetic discs that are stacked and laminated together into a cylindrical body. Each rotor disc has several openings that, when aligned with the openings of neighboring discs, form rotor slots that extend axially through the length of the rotor core. Persistent-state magnetic elements, such as permanent magnet bars, are inserted into the rotor core and secured within these rotor slots. The rotor core may be mounted onto a motor shaft for outputting propulsion-generating motor torque produced by the motor or for inputting electricity-generating regenerative torque received by the motor. During operation of the motor assembly, the internal electrical and electromagnetic hardware may generate a significant amount of heat, e.g., due to windage, friction, and hysteresis losses. An integrated motor cooling system may be employed to prevent undesirable overheating conditions within the motor. Active thermal management (ATM) systems, for example, employ a central controller or dedicated control module to regulate the operation of a cooling circuit that circulates coolant fluid through the heat-producing motor components. For indirect liquid cooling systems, a heat-transfer coolant is circulated through a network of internal channels and pipes within the motor housing. In contrast, direct liquid cooling systems—or "liquid immersion cooling" (LIC)—immerse the motor stator and windings within a direct-conduction dielectric liquid coolant.

SUMMARY

Presented herein are direct liquid cooling systems for permanent magnets of electric machines, methods for making and methods for operating such cooling systems, and motor vehicles equipped with IPM traction motors having rotor-encased permanent magnets cooled by such systems. By way of example, a multiphase ACPM motor contains a PM-bearing rotor assembly with a rotor core that is formed from a laminated stack of ferromagnetic discs. These stacked discs collectively define axially elongated rotor slots, which are arranged in sets of circumferentially spaced poles and secure therein discrete permanent magnets. The rotor core is keyed, splined, or otherwise drivingly engaged to a motor shaft with a hollow core through which dielectric coolant fluid is fed into the rotor assembly. Front and rear rotor discs at proximal and distal ends of the rotor core stack include radially elongated coolant feed grooves that transmit coolant fluid—under the centrifugal forces of the spinning rotor—from the motor shaft core to axially elongated coolant feed channels that are coterminous with the rotor slots. Each coolant feed groove may have a Y-shaped geometry with a stem ("descender") that fluidly connects to the motor shaft core and two branches ("diagonal strokes") that each fluidly connects to a respective pair of PM rotor slots. To ensure a continuous and even feed of coolant to each rotor slot, the bottom end of the stem may have an enlarged base section for receiving fluid, and the top end of the stem may have an enlarged trough section for pooling coolant fluid. Coolant is fed from the front disc and through a first subset of the axially elongated feed channels in a rearward direction, whereas coolant is fed from the rear disc and through a distinct second subset of the axially elongated feed channels in a forward direction.

Attendant benefits for at least some of the disclosed concepts include direct liquid cooling systems with optimized coolant conduit architectures for direct-contact cooling of target surfaces of rotor-mounted permanent magnets. Disclosed designs enable liquid coolant to be fed directly to the PM slots in the rotor core laminations to contact the magnets with a concomitant reduction in magnet operating temperatures. The unique coolant feed design in the end discs may enable coolant to reach all of the magnet slots during motor operation such that coolant flows across the entire axial length of every magnet slot and, thus, every magnet contained therein. The Y-shaped coolant grooves in the end discs are engineered to direct coolant to both branches by allowing coolant to pool in a trough at the center of the groove. This enables one Y-shaped coolant feed groove to transmit a metered supply of coolant to each of four or more PM rotor slots, which simplifies coolant plumbing, reduces coolant charge volumes, and reduces packaging requirements.

Aspects of this disclosure present direct liquid cooling systems for regulating the operating temperatures of magnets in electric machines, such as motors, generators, transformers, inductors, dynamometers, converters, etc. According to an example, there is presented an electric machine that is cooled by a direct liquid cooling system, which is controller-operated to circulate liquid coolant, such as a thermally conductive dielectric oil, through the electric machine. The electric machine includes a protective outer housing, a stator assembly that is rigidly mounted inside the housing, and a rotor assembly that is rotatably attached to the housing, coaxial with and spaced from the stator assembly. The stator assembly includes a stator core with one or more electromagnetic windings, such as U-shaped copper hairpins, mounted to the stator core. The rotor assembly includes a rotor core with one or more magnets, such as hard-ferrite permanent magnets, mounted to the rotor core. The rotor core defines therein one or more radially elongated rotor feed grooves that are fluidly connected to one or more axially elongated rotor feed channels. The rotor feed groove(s) fluidly connect to a direct liquid cooling system to receive therefrom a liquid coolant. Each rotor feed channel receives liquid coolant from the feed groove(s) and transports the coolant into direct contact with a target surface of a magnet.

Additional aspects of this disclosure are directed to electric-drive vehicles with multiphase brushless ACPM traction motors that contain rotor-mounted magnets cooled via direct liquid cooling. As used herein, the terms "vehicle" and "motor vehicle" may be used interchangeably and synonymously to include any relevant vehicle platform, such as passenger vehicles (ICE, HEV, FEV, fuel cell, fully and partially autonomous, etc.), commercial vehicles, industrial vehicles, tracked vehicles, off-road and all-terrain vehicles (ATV), motorcycles, farm equipment, watercraft, aircraft, etc. For non-automotive applications, disclosed concepts may be employed for any logically relevant use, including commercial or residential generators, turbines, pumping equipment, compressors, machine tools, alternators, etc. In an example, a motor vehicle includes a vehicle body with a passenger compartment, multiple road wheels mounted to the vehicle body (e.g., via corner modules coupled to a unibody or body-on-frame chassis), and other standard original equipment. For electric-drive vehicle applications, one or more electric traction motors operate alone (e.g., for FEV powertrains) or in conjunction with an internal combustion engine assembly (e.g., for HEV powertrains) to drive one or more of the road wheels and propel the vehicle.

Continuing with the preceding discussion, a direct liquid cooling system is packaged within the vehicle body and selectively operable to circulate liquid coolant through the traction motor(s). Each traction motor includes a protective motor housing that is attached to the vehicle body and rigidly mounts therein a stator assembly. The stator assembly includes a cylindrical stator core with a hollow center and axially elongated stator slots through which extend multiple electromagnetic windings. Rotatably mounted inside the motor housing is a PM-bearing rotor assembly that is located in the hollow center of the stator core, coaxial with and separated by an airgap from the stator assembly. The rotor assembly includes a rotor core with a hollow center and axially elongated rotor slots, each of which mounts therein a respective permanent magnet. The rotor core includes radially elongated rotor feed grooves that are fluidly connected to axially elongated rotor feed channels. Each rotor feed groove is fluidly connected to the direct liquid cooling system to receive therefrom liquid coolant. Each rotor feed channel transports the received liquid coolant to a respective one of the rotor slots and into direct contact with a target surface of the permanent magnet contained in the respective one of the rotor slots.

Aspects of this disclosure are also directed to manufacturing workflow processes, system control logic, and computer-readable media (CRM) for operating or for producing any of the disclosed rotor assemblies, electric machines, and/or vehicles. In an example, a method is presented for assembling an electric machine. This representative method includes, in any order and in any combination with any of the above and below disclosed options and features: receiving a housing of the electric machine; mounting a stator assembly inside the housing, the stator assembly including a stator core and an electromagnetic winding mounted to the stator core; rotatably mounting a rotor assembly inside the housing such that the rotor assembly is coaxial with and spaced from the stator assembly, the rotor assembly including a rotor core and a magnet mounted to the rotor core, the rotor core defining therein a radially elongated rotor feed groove fluidly connected to an axially elongated rotor feed channel; and, fluidly connecting the rotor feed groove to the direct liquid cooling system to receive therefrom the liquid coolant, wherein the rotor feed channel transports the liquid coolant into direct contact with a target surface of the magnet.

For any of the disclosed electric machines, vehicles, and methods, each rotor feed groove may have a Y-shaped geometry with a pair of branches projecting radially outward from a radially outer end of a stem. In this instance, the stem has a radially inner end, opposite its radially outer end, through which liquid coolant is fed into the rotor assembly. Each feed groove branch may be fluidly coupled with and feed liquid coolant to a respective one of the feed channels. As another option, each rotor feed groove may include a coolant trough that is interposed between and fluidly connects the stem and two branches. The coolant trough has an enlarged (first) lateral width that is greater than a narrow (second) lateral width of the stem's radially outer end. In this instance, the stem may include a base, which is located at the stem's radially inner end, and a column, which connects the base to the stem's radially outer end. The base may have a variable (third) lateral width that is greater than a fixed (fourth) lateral width of the column. The stem branches may project at an oblique angle from the radially outer end of the stem. Additionally, the stem may be curvilinear and the branches may be arcuate.

For any of the disclosed electric machines, vehicles, and methods, the rotor core may include multiple radially elongated coolant feed grooves that are recessed into and circumferentially spaced around an end surface of the rotor core. Likewise, the rotor core may include multiple axially elongated coolant feed channels that are circumferentially spaced around and extend entirely through the rotor core. As another option, the rotor core may include a stack of rotor discs with a front (first) end disc at a front (first) end of the rotor stack. In this instance, a front (first) set of coolant feed grooves may be recessed into, circumferentially spaced around, and extend radially outward along a front (first) surface of the front (first) end disc. The rotor core may also include a rear (second) end disc at a rear (second) end of the rotor stack. In this instance, a rear (second) set of feed grooves may be recessed into, circumferentially spaced around, and extends radially outward along a rear (second) surface of the rear (second) end disc. The rotor core may include a pair of (first and second) sets of rectilinear feed channels that extend axially through the rotor stack; each set of rectilinear coolant feed channels is fluidly connected to a respective set of Y-shaped coolant feed grooves. A pair of (first and second) annular end plates may each abut a respective one of the end discs and, in so doing, cover open axial faces of the feed grooves in that respective end disc.

For any of the disclosed electric machines, vehicles, and methods, the rotor assembly may contain multiple permanent magnets and the rotor core may define therethrough multiple axially elongated rotor slots, each of which secures therein a respective one of the permanent magnets. In this instance, the rotor core may include multiple axially elongated feed channels, each of which fluidly connects to and is coterminous with a respective one of the rotor slots, e.g., such that liquid coolant flows across and contacts the entire axial length of the PM. A motor shaft may be drivingly connected to the rotor core to rotate in unison with the rotor assembly. In this instance, the motor shaft defines therein an axially elongated coolant feed core through which liquid coolant is received from the direct liquid cooling system and transmitted into the rotor assembly. Each rotor feed groove may be fluidly connected to the coolant feed core.

The above summary does not represent every embodiment or every aspect of the present disclosure. Rather, the foregoing summary merely provides a synopsis of some of the novel concepts and features set forth herein. The above features and advantages, and other features and attendant advantages of this disclosure, will be readily apparent from the following Detailed Description of illustrated examples and representative modes for carrying out the disclosure when taken in connection with the accompanying drawings and appended claims. Moreover, this disclosure expressly includes any and all combinations and subcombinations of the elements and features presented above and below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of a representative electric-drive motor vehicle with a hybrid electric powertrain employing an internal combustion engine and an alternating-current, permanent magnet (ACPM) traction motor with which aspects of this disclosure may be practiced.

FIG. **2** is an end-view illustration of a representative interior permanent magnet (IPM) electric machine employing a hairpin-wound stator and a PM-bearing rotor with which aspects of this disclosure may be practiced.

FIG. **3** is an enlarged, perspective-view illustration of a representative IPM rotor assembly with a direct liquid cooling system for cooling internal permanent magnets in accord with aspects of the present disclosure.

FIG. **4** is sectional, side-view illustration of the representative IPM rotor assembly of FIG. **3** showing the internal coolant conduit architecture for feeding liquid coolant into direct contact with the rotor-borne internal permanent magnets.

The present disclosure is amenable to various modifications and alternative forms, and some representative embodiments of the disclosure are shown by way of example in the drawings and will be described in detail herein. It should be understood, however, that the novel aspects of this disclosure are not limited to the particular forms illustrated in the above-enumerated drawings. Rather, this disclosure covers all modifications, equivalents, combinations, permutations, groupings, and alternatives falling within the scope of this disclosure as encompassed, for example, by the appended claims.

DETAILED DESCRIPTION

This disclosure is susceptible of embodiment in many different forms. Representative embodiments of the disclosure are shown in the drawings and will herein be described in detail with the understanding that these embodiments are provided as an exemplification of the disclosed principles, not limitations of the broad aspects of the disclosure. To that extent, elements and limitations that are described, for example, in the Abstract, Introduction, Summary, and Detailed Description sections, but not explicitly set forth in the claims, should not be incorporated into the claims, singly or collectively, by implication, inference or otherwise. Moreover, recitation of "first", "second", "third", etc., in the specification or claims is not used to establish a serial or numerical limitation; rather, these designations may be used for ease of reference to similar features in the specification and drawings and to demarcate between similar elements in the claims.

For purposes of the present detailed description, unless specifically disclaimed: the singular includes the plural and vice versa; the words "and" and "or" shall be both conjunctive and disjunctive; the words "any" and "all" shall both mean "any and all"; and the words "including," "containing," "comprising," "having," and the like, shall each mean "including without limitation." Moreover, words of approximation, such as "about," "almost," "substantially," "generally," "approximately," and the like, may each be used herein in the sense of "at, near, or nearly at," or "within 0-5% of," or "within acceptable manufacturing tolerances," or any logical combination thereof, for example. Lastly, directional adjectives and adverbs, such as fore, aft, inboard, outboard, starboard, port, vertical, horizontal, upward, downward, front, back, left, right, etc., may be with respect to a motor vehicle, such as a forward driving direction of a motor vehicle when the vehicle is operatively oriented on a horizontal driving surface.

Referring now to the drawings, wherein like reference numbers refer to like features throughout the several views, there is shown in FIG. **1** a schematic illustration of a representative motor vehicle, which is designated generally at **10** and portrayed herein for purposes of discussion as an electric-drive passenger car with a parallel two-clutch (P2) hybrid-electric powertrain. The illustrated automobile **10**—also referred to herein as "motor vehicle" or "vehicle" for short—is merely an exemplary application with which aspects of this disclosure may be practiced. In the same vein, incorporation of the present concepts into a hybrid electric powertrain should also be appreciated as a representative implementation of the inventive concepts disclosed herein. As such, it should be understood that aspects of this disclosure may be applied to other powertrain architectures, may be incorporated into any logically relevant type of motor vehicle, and may be utilized for both automotive and non-automotive applications alike. Lastly, only select components of the motor vehicles and electric machines have been shown and will be described in additional detail below. Nevertheless, the vehicles and machines discussed herein may include numerous additional and alternative features, and other available peripheral components, for carrying out the various methods and functions of this disclosure.

The representative vehicle powertrain system of FIG. **1** is shown with a prime mover—represented herein by a restartable internal combustion engine (ICE) assembly **12** and an electric motor/generator unit (MGU) **14**—that drivingly connects to a driveshaft **15** of a final drive system **11** by a multi-speed automatic power transmission **16**. The engine **12** transfers power, typically by way of torque via an engine crankshaft **13**, to an input side of the transmission **16**. Engine torque is first transmitted via the crankshaft **13** to rotate an engine-driven torsional damper assembly **26**; transmitted engine torque is concurrently transferred through the torsional damper assembly **26** to an engine disconnect device **28**. This engine disconnect device **28**, when operatively engaged, transmits torque received from the ICE assembly **12**, by way of the damper **26**, to input structure of the torque converter (TC) assembly **18**. As the name implies, the engine disconnect device **28** may be selectively disengaged to drivingly disconnect the ICE **12** from the motor **14**, TC assembly **18**, and transmission **16**.

To propel the hybrid vehicle **10** of FIG. **1**, a multispeed power transmission **16** is adapted to receive, selectively manipulate, and distribute tractive power output from the engine **12** and motor **14** to the vehicle's final drive system **11**. The final drive system **11** is represented herein by a driveshaft **15**, a rear differential **22**, and a pair of rear drive wheels **20**. The power transmission **16** and torque converter **18** of FIG. **1** may share a common transmission oil pan or "sump" **32** for supply of hydraulic fluid. A shared transmission pump **34** provides sufficient hydraulic pressure for the fluid to selectively actuate hydraulically activated elements of the transmission **16**, the TC assembly **18** and, for some implementations, the engine disconnect device **28**.

The ICE assembly **12** operates to propel the vehicle **10** independently of the electric traction motor **14**, e.g., in an "engine-only" operating mode, or in cooperation with the motor **14**, e.g., in "vehicle-launch" or "motor-boost" operating modes. In the example depicted in FIG. **1**, the ICE assembly **12** may be any available or hereafter developed engine, such as a compression-ignited diesel engine or a spark-ignited gasoline or flex-fuel engine, which is readily adapted to provide its available power output typically at a number of revolutions per minute (RPM). Although not explicitly portrayed in FIG. **1**, it should be appreciated that the final drive system **11** may take on any available configuration, including front wheel drive (FWD) layouts, rear wheel drive (RWD) layouts, four-wheel drive (4WD) layouts, all-wheel drive (AWD) layouts, six-by-four (6×4) layouts, etc.

FIG. **1** also depicts an electric motor/generator unit ("motor") **14** that operatively connects via a rotor shaft, motor support hub, or belt (collectively motor output member **29**) to the hydrodynamic torque converter **18**. The torque converter **18**, in turn, drivingly connects the motor **14** to an input shaft **17** of the transmission **16**. The electric motor/generator unit **14** is composed of a cylindrical stator assembly **21** circumscribing and concentric with a cylindrical rotor assembly **23**. Electric power is provided to the stator **21** through a high-voltage electrical system, including electrical conductors/cables **27** that pass through the motor housing via suitable scaling and insulating feedthroughs (not illustrated). Conversely, electric power may be provided from the MGU **14** to an onboard traction battery pack **30**, e.g., during a regenerative braking mode. Operation of any of the illustrated powertrain components may be governed by an onboard or remote vehicle controller or module or network of controllers/modules/devices, all variations of which are represented in FIG. **1** by a programmable electronic control unit (ECU) **25**.

Power transmission **16** may use differential gearing **24** to achieve selectively variable torque and speed ratios between transmission input and output shafts **17** and **19**, respectively. One form of differential gearing is the epicyclic planetary gear arrangement, which offers the advantage of compactness and different torque and speed ratios among members of the planetary gearing. Traditionally, hydraulically actuated torque establishing devices, such as clutches and brakes, are selectively engageable to activate the aforementioned gear elements for establishing desired forward and reverse speed ratios between the transmission's input and output shafts **17**, **19**. While envisioned as a 6-speed or 8-speed automatic transmission, the power transmission **16** may optionally take on other functionally appropriate configurations, including Continuously Variable Transmission (CVT) architectures, manual or automated-manual transmissions, etc.

Hydrodynamic torque converter assembly **18** of FIG. **1** operates as a fluid coupling for operatively connecting the engine **12** and motor **14** with the internal epicyclic gearing **24** of the power transmission **16**. Disposed within an internal fluid chamber of the torque converter assembly **18** is a bladed impeller **36** facing a bladed turbine **38**. The impeller **36** is juxtaposed in serial power-flow fluid communication with the turbine **38**, with a TC stator (not shown) interposed between the impeller **36** and turbine **38** to selectively alter fluid flow therebetween. The transfer of torque from the engine and motor output members **13**, **29** to the transmission **16** via the TC assembly **18** may be through stirring excitation of hydraulic fluid, such as transmission oil, inside the TC's internal fluid chamber caused by rotation of the impeller and turbine **36**, **38** blades. To protect these components, the torque converter assembly **18** is constructed with a TC pump housing, defined principally by a transmission-side pump shell **40** that is fixedly attached to an engine-side pump cover **42** such that a working hydraulic fluid chamber is formed therebetween.

FIG. **2** illustrates an example of an electric machine **114** that employs persistent-state magnetic materials that exchange electromagnetic forces with electrically conductive windings to convert electrical energy into mechanical energy, and vice versa. The electric machine **114** has a multiphase, hairpin-wound stator assembly **116** that nests therein and circumscribes a PM-bearing synchronous reluctance rotor assembly **118**. While available for use in automotive and non-automotive applications alike, the electric machine **114** of FIG. **2** may be particularly suited for use in a hybrid-electric powertrain as a traction motor (e.g., motor **14** FIG. **1**) with an engine (e.g., ICE assembly **12**), and to operate in at least an engine-cranking mode, a regenerative-charging mode, and a torque-assist mode. Electric machine

114 may be designed to achieve: a relatively high efficiency, such as at least about 85% efficiency over a calibrated output power and speed range; a relatively high power density (e.g., greater than about 1500 watts per liter) and torque density (e.g., greater than about 5 Newton-meters per liter); a relatively wide peak power range (e.g., about 4 to 6 kilowatts or greater); a maximum speed of at least about 18,000 rpm; a reduced mass and inertia (e.g., for fast dynamic response to user output demands); and to fit into a relatively small packaging space. Innumerable alternative architectures may be employed by the electric machine **114** to meet similar and alternative operating parameters. For instance, FIG. **2** portrays the electric machine **114** with interior magnets arranged in a U-shaped pattern; however, disclosed concepts may be applied to other magnet patterns, such as the V-shaped pattern illustrated in FIG. **3**.

With continuing reference to FIG. **2**, the stator assembly **116** is coaxial with and surrounds the rotor assembly **118** while maintaining a small airgap **115** therebetween. In accord with the illustrated example, this airgap **115** may be not less than about 0.2 millimeters (mm) and not greater than about 1.0 mm, for example, in order to maximize power output and minimize the number of permanent magnets **120** borne by the rotor assembly **118** to provide a desired power output. The representative stator and rotor assemblies **116**, **118** of FIG. **2** are concentrically aligned about a shared longitudinal center axis A of the electric machine **114**. The stator assembly **116** has a hollow stator core **126** with a central bore **122** that nests therein the rotor assembly **118**. The rotor assembly **118** has a hollow rotor core **128**, e.g., that keys, splines, welds, etc., to a motor shaft (e.g., motor output member **29** of FIG. **1**). It should be appreciated that a protective motor housing (shown schematically at **31** in FIG. **1**) may surround an outer periphery of the stator assembly **116** and can rotatably support the rotor and rotor output shaft of the electric machine **114**.

Rotor assembly **118** of FIG. **2** is fabricated with a rotor core **128**, which may have a right-circular cylinder geometry with a generally annular shape, for supporting multiple permanent magnets **120** (twenty-four (24) PMs in the illustrated example) that are circumferentially spaced around a central bore **124**. Specifically, the rotor core **128** is stamped, precision machined, and assembled with multiple rotor slots **130** arranged in radially spaced barrier layers (e.g., four distinct barrier layers). A first barrier layer **130**A of slots **130** may be positioned closest to an inner periphery of the rotor core **128**, while a fourth barrier layer **130**D of slots **130** may be positioned furthest from the rotor body's inner periphery than the other barrier layers. A second barrier layer **130**B may be radially interposed between the first and third barrier layers **130**A, **130**C, while a third barrier layer **130**C may be radially interposed between the second and fourth barrier layers **130**B, **130**D. For at least some embodiments, only select barrier layers (e.g., the first and third barrier layers **130**A, **130**C) may house magnets **120**, while other select barrier layers (e.g., the second and fourth barrier layers **130**B. **130**D) do not house magnets **120** and, thus, act as flux barriers. In other embodiments, only one or all of the barrier layers may comprise slots storing therein permanent magnets. The rotor core **128** may be fabricated from metallic disc-shaped laminates, including high-grade steel materials, that are stacked and adhered together to maintain high-speed rotational stress within predetermined limits.

Stator assembly **116** of FIG. **2** is fabricated with a stator core **126**, which may also have a right-circular cylinder geometry with a generally annular shape and may have multiple radially aligned, axially elongated, and circumferentially spaced stator slots **132** (e.g., 60 total slots in the illustrated example). Each stator slot **132** extends longitudinally through the stator core **126**, parallel to the rotational axis A of the electric machine **114**. The stator slots **132** house complementary legs of electrically conductive, multiphase stator windings **134**. Stator windings **134**—also referred to herein as "hairpin windings"—may be grouped into different sets, each of which may carry an identical number of phases of electrical current, such as three, five, six, or seven phases. In addition, the stator windings **134** may extend axially beyond the longitudinal ends of the stator core **126**. A ratio of an outer diameter of the stator core **126** to an axial length of the stator core **126** may be not less than 1.5 and not greater than 3.5, for example, to satisfy packing space constraints for a desired application of the electric machine **114**, such as the vehicle powertrain of FIG. **1**.

For case of manufacture and simplicity of design, it may be desirable that all of the permanent magnets **120** share an identical, rectangular polyhedron shape. Nevertheless, any one or more or all of the PM bodies may take on innumerable shapes and sizes, including other polyhedral block-type magnets, ring-shaped (annular) magnets, bread-loaf block-type magnets, curved tile magnets, etc. In a non-limiting example, each permanent magnet **120** may have a thickness of about 1.5 mm to 2.5 mm to fit within a slot **130** having complementary dimensions. A total mass of magnet material used by the electric machine **114** (i.e., the mass of all magnets **120**) may be about 150 grams to about 250 grams. The permanent magnets **120** of the electric machine **114** may all be fabricated from the same material, such as Neodymium Iron Boron (NdFeB); alternatively, the magnets **120** may employ different materials, such as Samarium Cobalt (SmCo), Aluminum Nickel Cobalt (AlNiCo), or any combination of rare earth magnet materials.

Similar to the permanent magnets **120** of FIG. **2**, it may be desirable that all of the multiphase stator windings **134** share an identical construction, including material composition, method of manufacture, and final geometry. Each stator winding **134** may be fabricated from a unitary bar conductor, which is formed into a U-shaped geometry that is defined by a pair of hairpin legs that project from opposing ends of a hairpin crown. The hairpin legs are inserted into the slots **132** of the stator core **126**, with each leg extending through a different stator slot **132** such that the hairpin crown (or "end-turn") extends over several of the stator slots **132** (e.g., each crown may extend across three or more slots). These hairpin windings **134** may be inserted in a "staggered" or "interleaved" pattern with respect to adjacent hairpins. Any given stator slot **132** may contain a number of hairpin legs (e.g., four in FIG. **2**). Once all of the hairpin windings **134** are inserted into the slots **132** of the stator core **126**, the ends of the hairpin legs extending from a longitudinal end of the stator core **126** are bent. Electrical connections are then made to each winding **134**.

During operation of the electric machine **114**, e.g., in a regenerative-charging mode, the rotor assembly **118** is rotated via the rotor output shaft while the stator assembly **116** is held relatively stationary. In so doing, the permanent magnets **120** are moved past the multiphase stator windings **134**; the magnetic field emitted by the permanent magnets **120** generates an electrical current in the windings **134** through electromagnetic induction. This induced electric current may be used to power a load (e.g., recharge traction battery pack **30** of FIG. **1**). Conversely, during operation of the electric machine **114**, e.g., in an engine-cranking mode, an EV motoring mode, or a torque-assist mode, an electric current is supplied to the stator windings **134** by a suitable power source (e.g., traction battery pack **30**). Passing the supplied current through the multiphase stator windings **134** will generate a magnetic field at radially inward ends of stator teeth **136**. The magnetic field output from these stator teeth **136** interacts with the permanent magnets **120** in the rotor assembly **118** such that the rotor core **128** and attached shaft rotate in unison to generate a rotary driving force.

During operation of the electric machine **114**, the internally mounted permanent magnets **120** may be subjected to a significant amount of motor-borne heat, for example, from rotor bearing friction, air-to-rotor "windage" friction, electrified winding resistance, core hysteresis, etc. To mitigate PM heat, there are disclosed herein direct liquid cooling systems, methods, and devices for directing liquid coolant to the rotor slots and into direct contact with one or more target surfaces of each magnet. The rotor core contains a unique design of internal coolant channels in the end discs and rotor disc stack that may collectively enable coolant to reach all rotor slots and magnets during motor operation. With these designs, coolant may flow across the entire axial length of the rotor core and the rotor slots. Also disclosed are unique Y-shaped coolant grooves that enable coolant to be directed to multiple rotor slots from a single coolant groove by allowing coolant to pool at the interface of the stem and branches and enabling coolant to "spill" into both branches. As shown, Y-shaped coolant grooves with center coolant troughs enable a single coolant groove to supply four (4) or more magnet slots, which reduces packaging space and coolant charge requirements. Magnet temperature in an IPM motor may be reduced by pumping liquid coolant into an inner diameter (ID) coolant feed core of a rotor shaft, out through radial holes in the rotor shaft, through coolant feed grooves in the end discs of the rotor core stack, into and across coolant feed channels coterminous with the PM-bearing rotor slots, and out through coolant exhaust holes in end plates at terminal ends of the stack.

Turning next to FIG. **3**, there is shown a perspective-view illustration of a representative stacked-laminate IPM rotor assembly **218** that is cooled by direct liquid cooling system **250** (FIG. **4**) that is controller-operated to actively circulate a liquid coolant **252**, such as an engineered full-immersion coolant or a lubricating dielectric oil (e.g., pumped from transmission oil pan **32**). Although differing in appearance, it is envisioned that any of the related features and options described above with respect to the motor assembly **14** and electric machine **114** of FIGS. **1** and **2** can be incorporated, singly or in any combination, into the IPM rotor assembly **218** of FIGS. **3** and **4**, and vice versa. As a non-limiting point of similarity, the rotor assembly **218** of FIG. **3** is rotatably mounted (e.g., via a pair of high-speed roller bearings) inside a protective outer housing (e.g., motor housing **31** of FIG. **1**) such that the rotor assembly **218** is coaxial with and spaced across an airgap from an electromagnetic stator assembly (e.g., hairpin-wound stator assembly **116**). To that end, the rotor assembly **218** of FIG. **3** may be adapted for use in the electric traction motor **14** of FIG. **1**, e.g., for automotive applications, or in the electric machine **114** of FIG. **2**, e.g., for non-automotive applications.

The rotor assembly **218** of FIGS. **3** and **4** is generally composed of a hollow, cylindrical rotor core **228** with one or more magnets—sixteen (16) large PMs **220**A paired with sixteen (16) small PMs **220**B in FIG. **4**—that are mounted to the rotor core **228**. The rotor core **228** may be fabricated as a multilayer laminate construction that, as the name implies, is typified by a laminated stack **254** of rotor discs **256**. While depicted as having a total of twelve (12) rotor disc laminates, the rotor core **228** stack **254** may comprise greater or fewer laminations than what is shown, typically between about 30 to about 70 individual laminations each having an axial thickness of between about 1.5 mm and about 3.0 mm. In this regard, the rotor core **228** may have an axial length of about 40 mm to about 80 mm and an outer diameter of about 120 mm to about 195 mm. Each of the rotor core **228** rotor discs **256** may be fabricated from a suitable ferromagnetic material, such as electrical steel, iron, nickel, cobalt, combinations thereof, or the like. Annular endplates **258**A and **258**B may be pressed against opposing ends of the laminate stack **254** to retain the laminations in place during operation of the electric machine. When stacked and operatively aligned, the rotor discs **256** collectively define through the rotor core **228** multiple axially elongated rotor slots—sixteen (16) large slots **230**A paired with sixteen (16) small slots **230**B in FIG. **3**—each securing therein a respective one of the permanent magnets **220**A, **220**B.

FIG. **4** illustrates a bore-mounted rotor shaft **260** (also referred to herein as "motor shaft" for electric motor applications) that is splined, keyed, or otherwise drivingly connected to the rotor core **228** to thereby rotate in unison with the rotor assembly **218**. In accord with the illustrated example, the rotor shaft **260** is inserted into and projects outward from open ends of a central bore **224** that extends axially through the laminated stack **254** of rotor discs **256**. The rotor shaft **260** may be rotatably supported on high-speed axial roller bearings (not shown) that seat on rotor shaft bearing journals **261**A and **261**B and align the rotor assembly **218** with respect to its mating stator assembly while enabling rotation of the rotor **218** and shaft **260**, i.e., to transmit and/or receive torque. An axially elongated coolant feed core **263** is formed or machined into the center of the rotor shaft **260**. The shaft core **263** is shown in FIG. **4** as a blind-type hole with an open proximal end, which extends through a proximal end of the shaft **260**, and a closed distal end, which terminates axially inward from a distal end of the shaft **260**. Press-fit into the open proximal end of the coolant feed core **263** is a coolant supply nozzle **265** through which liquid coolant **252** is pumped via a coolant pump **262** from a coolant tank **264** into the rotor shaft **260**. A coolant flow split tube **267** is secured inside the coolant feed core **263**, fluidly downstream from the coolant supply nozzle **265**; the split tube **267** facilitates the dividing and dissemination of coolant **252** through radial feed holes **269** in the rotor shaft **260**.

To transmit liquid coolant **252** from the cooling system **250** into direct contact with the rotor-mounted PMs **220**A, **220**B, the rotor core **228** contains one or more radially elongated rotor feed grooves **266** that transfer coolant **252** from the rotor shaft **260** to the rotor slots **230**A, **230**B. By way of non-limiting example, the rotor assembly **218** of FIG. **3** may include eight (8) rotor feed grooves **266** with four (4) grooves **266** recessed into and circumferentially spaced equidistant from one another around each axial end surface of the rotor core **228**. For laminate-stack constructions, a front (first) end disc **256**A at a front (first) end of the rotor laminate stack **254** is formed or machined with a front (first) set of coolant feed grooves **266**A that is recessed into, circumferentially spaced around, and extend radially outward along a forward-facing (first) surface of the front (first) end disc **256**A. In the same vein, a rear (second) end disc **256**B at a rear (second) end of the rotor stack **254** is formed or machined with a rear (second) set of feed grooves **266**B that is recessed into, circumferentially spaced around, and extend radially outward along a rearward-facing (second) surface of the rear (second) end disc **256**B. For simplicity of design and manufacture, it may be desirable that the two end discs **256**A, **256**B be structurally identical to each other (as shown in FIG. **3**) but stacked with their respective groove-bearing surfaces facing in opposite directions. A front (first) end plate **258**A abuts the groove-bearing surface of the front (first) end disc **256**A and covers the open axial faces of the feed grooves **266**A, whereas a rear (second) end plate **258**B abuts the groove-bearing surface of the rear (second) end disc **256**B and covers the open axial faces of the feed grooves **266**B. Each coolant feed groove **266** may fluidly connect to a respective coolant feed hole **269** of the rotor shaft **260** to thereby receive liquid coolant **252** from the direct liquid cooling system **250**.

In order to enable a single coolant feed groove **266** to supply liquid coolant **252** to multiple rotor slots **230**A, **230**B, each feed groove **266** may have a Y-shaped geometry with an elongated stem **271** that is integral with a pair of elongated branches **273**. The branches **273** project radially outward from a radially outer (top) end of the stem **271**, but terminate radially inward from an outer circumference of the rotor core **228**. A radially inner (bottom) end of each stem **271**, opposite that of the branches **273**, aligns with and fluidly couples to one of the feed holes **269** in the rotor shaft **260** to receive therefrom the liquid coolant **252**. At radially outer ends of the feed grooves **266**, each branch **273** fluidly connects to one or more respective rotor feed channels **268** and, thus, one or more respective rotor slots **230**A, **230**B. In accord with the example illustrated in FIG. **3**, the branches **273** may project in opposite direction from each other and thereby cooperatively define a W-shaped profile. Each branch **273** may project at an oblique angle from the stem **271** (e.g., approximately 40-70 degrees clockwise or counterclockwise from a linear radial line extending from the center rotational axis through the radially outer end of the stem **271**). As shown, the stem **271** has an S-shaped curvilinear geometry whereas the branches **273** each has an L-shaped arcuate geometry.

To ensure that liquid coolant **252** is distributed through all branches **273** and, thus, to all coolant feed channels **268** during rotation of the rotor assembly **218**, each coolant feed groove **266** may incorporate an integral coolant trough **275** that is interposed between and fluidly connects the stem **271** and branches **273**. The coolant trough **275** may have an enlarged (first) lateral width W_{C1} that is greater than a narrow (second) lateral width W_{C2} of the radially outer end of the stem **271**. This enlarged width creates a volumetric expansion in the coolant flow path that allows the coolant **252** to reduce speed and pool in the trough **275**; as the rotor assembly **218** spins, centrifugal forces cause the coolant **252** to spill from both sides of the trough **275** into the two branches **273**, which may be narrower in width than the trough **275**. It is envisioned that the coolant feed groove(s) **266** may also or alternatively be integrated into the endplates **258**A, **258**B.

In order to facilitate the transfer of coolant **252** from the rotor shaft **260** into the rotor assembly **218**, each of the coolant feed grooves **266** may incorporate an integral widened base **277** at the radially inner end of the stem **271** and an integral column that fluidly connects the base **271** to the radially outer end of the stem **271**. To progressively increase fluid speed of coolant **252** entering the coolant groove **266**, the base **277** may have a variable (third) lateral width W_{C3} that is greater than a fixed (fourth) lateral width W_{C4} of the stem column. The lateral width W_{C3} of the base **277** may progressively decrease in a radially outward direction to create a fluid construction that amplifies fluid flow speed. As shown, the lateral width W_{C4} of the stem's column may be substantially equal to the lateral width W_{C2} of the stem's radially outer end, and the lateral width of the branches **273** may be substantially equal to the lateral width W_{C2} of the stem's radially outer end. In the above discussion, each "lateral width" extends crosswise in the circumferential direction with respect to the axial end face of the rotor core **228**.

With collective reference to both FIGS. **3** and **4**, each coolant feed groove **266** is fluidly coupled to at least one or, as shown, four (4) axially elongated coolant feed channels **268** that transport liquid coolant **252** into direct contact with one or more target surfaces of each magnet **220**A, **220**B. For at least some applications, the rotor assembly **218** may employ a dedicated feed channel **268** for each PM **220**A, **220**B (e.g., thirty-two (32) feed channels in FIG. **3**). To that end, each feed channel **268** may adjoin and extend coterminous with a respective one of the rotor slots **230**A, **230**B. Similar to the rotor slots **230**A, **230**B, the coolant feed channels **268** are circumferentially spaced around and extend entirely through the rotor core **228**. One fore-aft (first) set of the rectilinear feed channels **268** extends axially through the rotor stack **254** and fluidly connects to the first set of feed grooves **266**A to transmit coolant **252** in a left-to-right (first) direction. By comparison, another fore-aft (second) set of the rectilinear feed channels **268** extends axially through the rotor stack **254** and fluidly connects to the second set of feed grooves **266**B to transmit coolant **252** in a right-to-left (second) direction, which is opposite that of the first feed grooves **266**A.

To evacuate liquid coolant **252** that has been heated through direct physical contact with the PMs **220**A, **220**B, each of the endplates **258**A, **258**B includes one or more coolant exit holes **270** through which spent coolant **252** is expelled from the rotor assembly **218**. As shown, there are eight (8) coolant exit holes **270** (i.e., one for each magnet pole) that are circumferentially spaced around and extend axially through each endplate **258**A, **258**B. A discrete coolant manifold channel **272** may connect each neighboring pair of coolant exit holes **270** to allow coolant **252** to simultaneously flow out of four (4) of the coolant feed channels **268** (e.g., depending on a rotation direction of the rotor assembly **218**, coolant **252** may accumulate in the manifold channel **272** and exit through one of the two interconnected exit holes **270**. The manifold channels **272** may be formed in the same surface as the coolant feed grooves **266**. It should be appreciated that the rotor assembly **218** of FIGS. **3** and **4** may incorporate greater or fewer coolant feed grooves and coolant feed channels with similar or alternative configurations and dimensions to that which are shown in the drawings without departing from the intended scope of this disclosure.

Aspects of the present disclosure have been described in detail with reference to the illustrated embodiments; those skilled in the art will recognize, however, that many modifications may be made thereto without departing from the scope of the present disclosure. The present disclosure is not limited to the precise construction and compositions disclosed herein; any and all modifications, changes, and variations apparent from the foregoing descriptions are within the scope of the disclosure as defined by the appended claims. Moreover, the present concepts expressly include any and all combinations and subcombinations of the preceding elements and features.

What is claimed:

1. An electric machine cooled by a liquid coolant circulated via a direct liquid cooling system, the electric machine comprising:

a housing;

a stator assembly located inside the housing and including a stator core and an electromagnetic winding mounted to the stator core; and

a rotor assembly rotatably attached to the housing coaxial with and spaced from the stator assembly, the rotor assembly including a rotor core and a magnet mounted to the rotor core, the rotor core defining therein a radially elongated rotor feed groove fluidly connected to an axially elongated rotor feed channel, the rotor feed groove configured to fluidly connect to the direct liquid cooling system to receive therefrom the liquid coolant, and the rotor feed channel transporting the liquid coolant into direct contact with a target surface of the magnet,

wherein the rotor core includes a rotor stack of rotor discs with a first end disc at a first end of the rotor stack, and wherein the rotor feed groove includes a first set of feed grooves recessed into, circumferentially spaced around, and extending radially outward along a first surface of the first end disc.

2. The electric machine of claim **1**, wherein at least one feed groove in the first set of feed grooves has a Y-shaped geometry with a stem and a pair of branches projecting from a radially outer end of the stem, the stem having a radially inner end opposite the radially outer end through which the liquid coolant is fed into the rotor assembly, and wherein the rotor feed channel includes multiple feed channels with each of the branches fluidly connected to a respective one or more of the feed channels.

3. The electric machine of claim **2**, wherein the at least one feed groove further includes a coolant trough interposed between and fluidly connecting the stem and the branches, the coolant trough having a first lateral width greater than a second lateral width of the radially outer end of the stem.

4. The electric machine of claim **3**, wherein the stem further includes a base at the radially inner end and a column connecting the base to the radially outer end of the stem, the base having a third lateral width greater than a fourth lateral width of the column.

5. The electric machine of claim **2**, wherein the branches project at an oblique angle from the radially outer end of the stem.

6. The electric machine of claim **2**, wherein the stem is curvilinear and the branches are arcuate.

7. The electric machine of claim **1**, wherein the rotor feed channel includes a plurality of coolant feed channels circumferentially spaced around and extending entirely through the rotor core.

8. The electric machine of claim **1**, wherein the rotor core further includes a second end disc at a second end of the rotor stack, and the rotor feed groove further includes a second set of feed grooves recessed into, circumferentially spaced around, and extending radially outward along a second surface of the second end disc.

9. The electric machine of claim **8**, further comprising first and second annular end plates abutting the first and second end discs, respectively, and covering open axial faces of the first and second sets of feed grooves, respectively.

10. The electric machine of claim **9**, wherein the rotor feed channel includes first and second sets of rectilinear feed channels extending axially through the rotor stack, the first set of rectilinear feed channels being fluidly connected to the first set of feed grooves, and the second set of rectilinear feed channels being fluidly connected to the second set of feed grooves.

11. The electric machine of claim **1**, wherein the magnet includes multiple permanent magnets, the rotor core defines therethrough multiple axially elongated rotor slots each securing therein a respective one of the permanent magnets, and the rotor feed channel includes multiple feed channels each fluidly connected to and coterminous with a respective one of the rotor slots.

12. The electric machine of claim **1**, further comprising a rotor shaft drivingly connected to the rotor core to rotate in unison with the rotor assembly, the rotor shaft defining therein an axially elongated coolant feed core through which the liquid coolant is transmitted into the rotor assembly, the rotor feed groove being fluidly connected to the coolant feed core.

13. A motor vehicle, comprising:

a vehicle body;

a plurality of road wheels rotatably attached to the vehicle body;

a direct liquid cooling system attached to the vehicle body and operable to circulate a liquid coolant; and

a traction motor attached to the vehicle body and operable to drive one or more of the road wheels to thereby propel the motor vehicle, the traction motor including:

a motor housing attached to the vehicle body;

a stator assembly rigidly mounted inside the motor housing, the stator assembly including a plurality of electromagnetic windings and a cylindrical stator core, the cylindrical stator core including a hollow center and a plurality of axially elongated stator slots through which extend the electromagnetic windings; and

a rotor assembly rotatably mounted inside the motor housing and located in the hollow center of the stator core coaxial with and separated by an airgap from the stator assembly, the rotor assembly including a plurality of permanent magnets and a cylindrical rotor core, the cylindrical rotor core including a hollow center and a plurality of axially elongated rotor slots each mounting therein a respective one of the permanent magnets, the rotor core defining therein a plurality of radially elongated rotor feed grooves fluidly connected to a plurality of axially elongated rotor feed channels, the rotor feed grooves being fluidly connected to the direct liquid cooling system to receive therefrom the liquid coolant, and each of the rotor feed channels transporting the liquid coolant to a respective one of the rotor slots and into direct contact with a target surface of the permanent magnet contained in the respective one of the rotor slots,

wherein the rotor core includes a rotor stack of rotor discs with a first end disc at a first end of the rotor stack, and wherein the rotor feed grooves include a first set of feed grooves recessed into, circumferentially spaced around, and extending radially outward along a first surface of the first end disc.

14. A method of assembling an electric machine cooled by a liquid coolant circulated via a direct liquid cooling system, the method comprising:

receiving a housing of the electric machine;

mounting a stator assembly inside the housing, the stator assembly including a stator core and an electromagnetic winding mounted to the stator core;

rotatably mounting a rotor assembly inside the housing such that the rotor assembly is coaxial with and spaced from the stator assembly, the rotor assembly including a rotor core and a magnet mounted to the rotor core, the rotor core defining therein a radially elongated rotor feed groove fluidly connected to an axially elongated rotor feed channel, the rotor core including a rotor stack of rotor discs with a first end disc at a first end of the rotor stack, and the rotor feed groove including a first set of feed grooves recessed into, circumferentially spaced around, and extending radially outward along a first surface of the first end disc; and

fluidly connecting the rotor feed groove to the direct liquid cooling system to receive therefrom the liquid coolant, wherein the rotor feed channel transports the liquid coolant into direct contact with a target surface of the magnet.

15. The method of claim **14**, wherein at least one feed groove in the first set of feed grooves has a Y-shaped geometry with a stem and a pair of branches projecting from a radially outer end of the stem, the stem having a radially inner end opposite the radially outer end through which the liquid coolant is fed into the rotor assembly, and wherein the rotor feed channel includes multiple feed channels with each of the branches fluidly connected to a respective one or more of the feed channels.

16. The method of claim **15**, wherein the at least one feed groove further includes a trough interposed between and fluidly connecting the stem and the branches, the trough having a first lateral width greater than a second lateral width of the radially outer end of the stem.

17. The method of claim **14**, wherein the rotor core further includes a second end disc at a second end of the rotor stack, and the rotor feed groove further includes a second set of feed grooves recessed into, circumferentially spaced around, and extending radially outward along a second surface of the second end disc.

18. The method of claim **14**, wherein the magnet includes multiple permanent magnets, the rotor core defines there-through multiple axially elongated rotor slots each securing therein a respective one of the permanent magnets, and the rotor feed channel includes multiple feed channels each fluidly connected to and coterminous with a respective one of the rotor slots.

19. The method of claim **14**, wherein the rotor assembly further includes a first end plate abutting the first end disc and covering the first set of feed grooves.

20. The method of claim **14**, wherein the rotor feed channel includes a first set of rectilinear feed channels circumferentially spaced around and extending axially through the rotor stack, the first set of rectilinear feed channels being fluidly connected to the first set of feed grooves.

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