US 20130175022A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2013/0175022 A1
(43) Pub. Date: Jul. 11, 2013

King et al.

(54) **THERMAL MANAGEMENT SYSTEM FOR BATTERY ELECTRIC VEHICLE**

(76) Inventors: **Jonathan King**, Novi, MI (US); **Rick Rajaie**, Rochester Hills, MI (US); **Richard A. DeVogelaere**, Novi, MI (US); **Adam J. Naish**, Novi, MI (US)

(21) Appl. No.: **13/823,176**

(22) PCT Filed: **Sep. 15, 2011**

(86) PCT No.: **PCT/US11/51673**

§ 371 (c)(1),
(2), (4) Date: **Mar. 14, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/385,656, filed on Sep. 23, 2010.

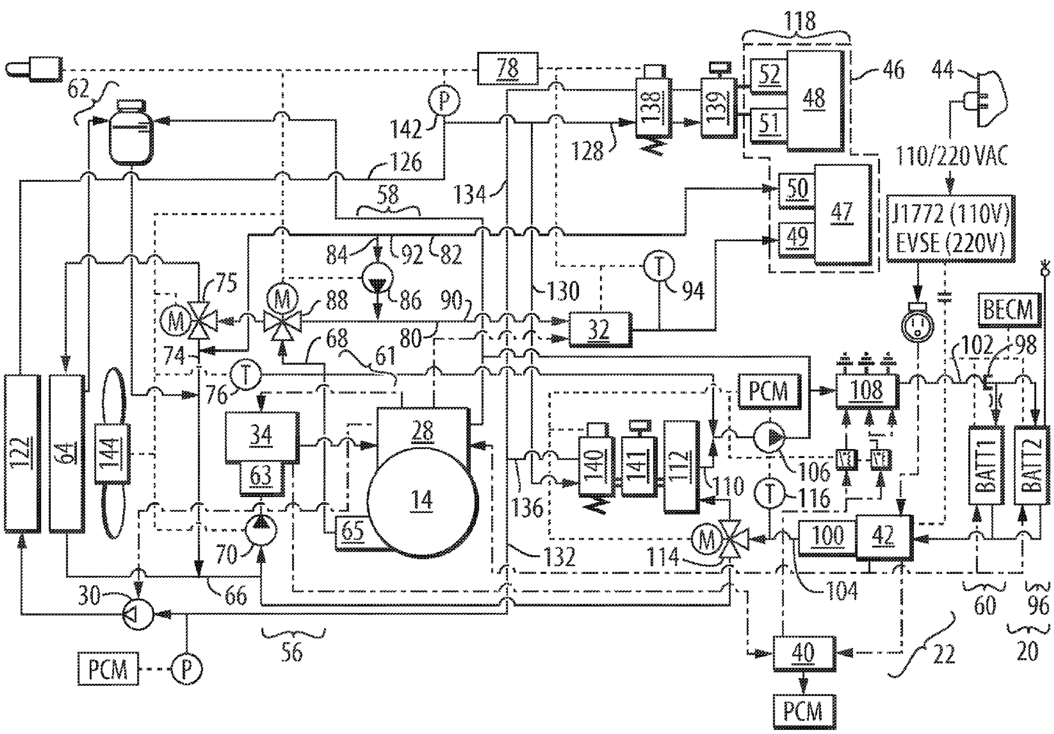
Publication Classification

(51) **Int. Cl.**
B60H 1/00 (2006.01)
B60H 1/03 (2006.01)

(52) **U.S. Cl.**
CPC ***B60H 1/00278*** (2013.01); ***B60H 1/034*** (2013.01); ***B60H 1/00885*** (2013.01)
USPC .... **165/202**; 165/43; 237/12.3 B; 236/34.5

(57) **ABSTRACT**

A thermal management system for an electric vehicle includes a motor circuit for cooling a motor circuit thermal load, a cabin heating circuit for heating a cabin heater and a battery circuit for managing the temperature of a battery circuit thermal load. All of these circuits can fluidically communicate with each other and a single radiator can cool the fluid from all of these circuits.



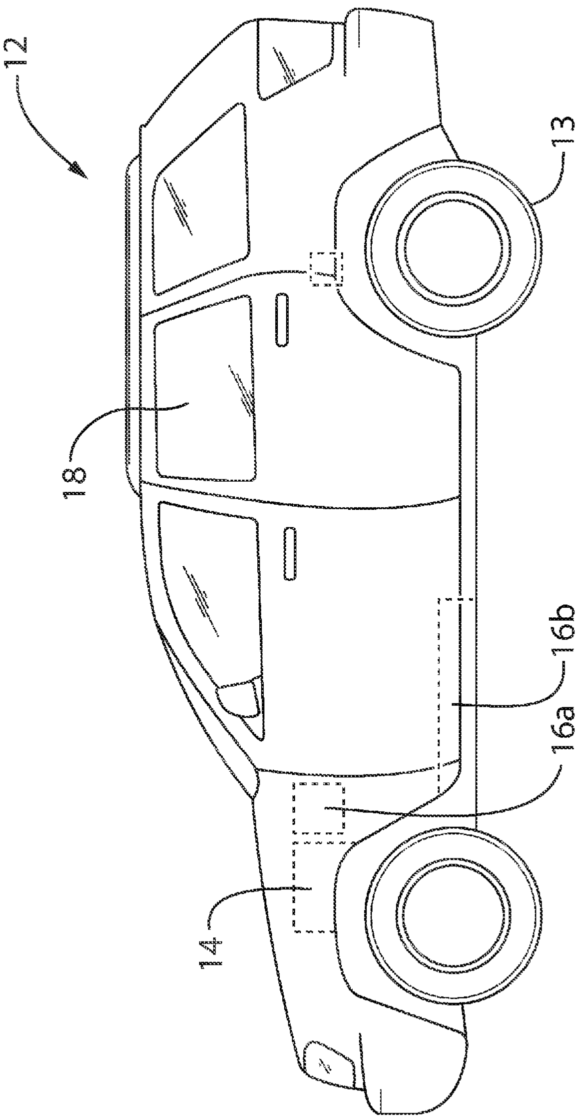


FIG. 1

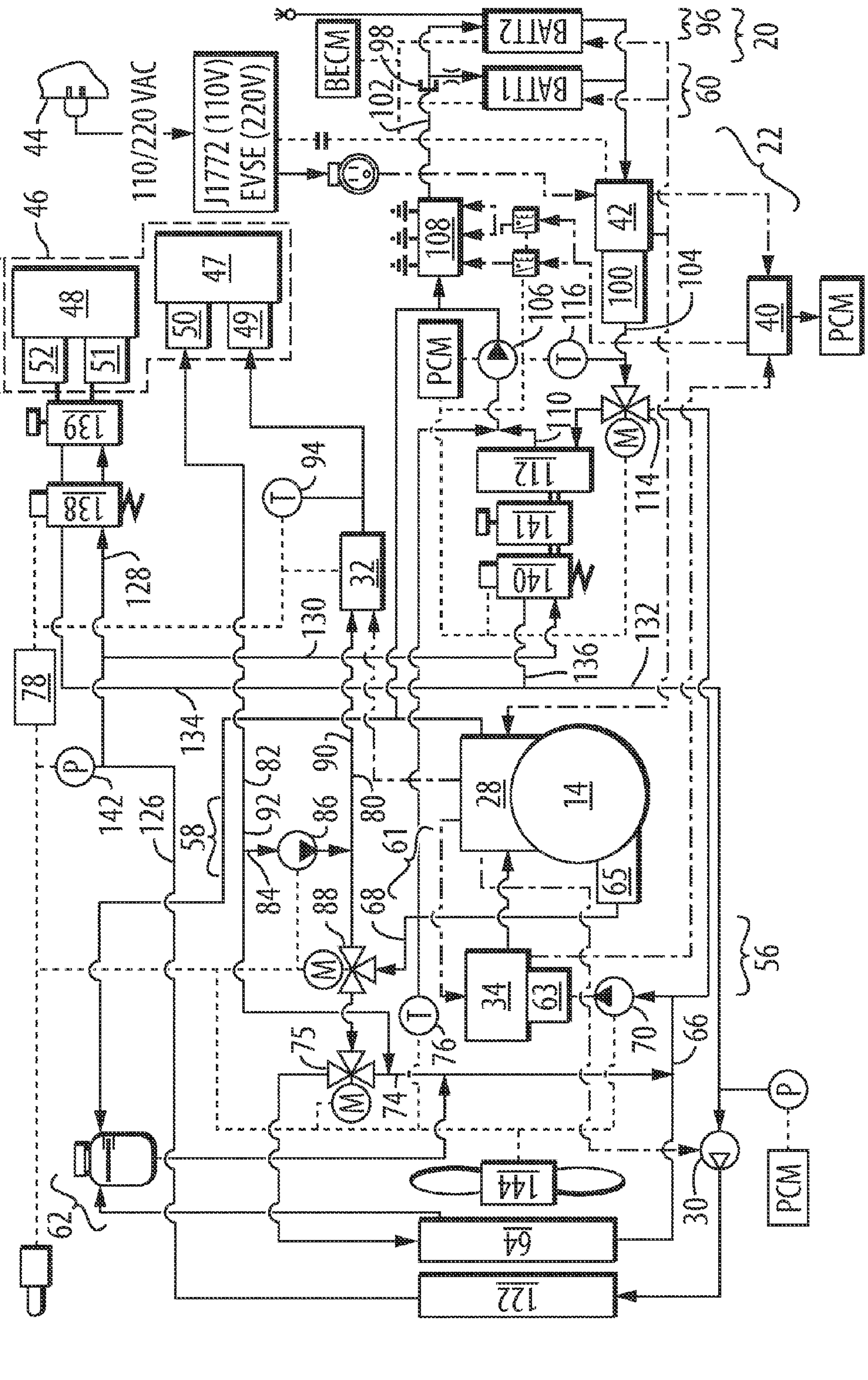


FIG. 2

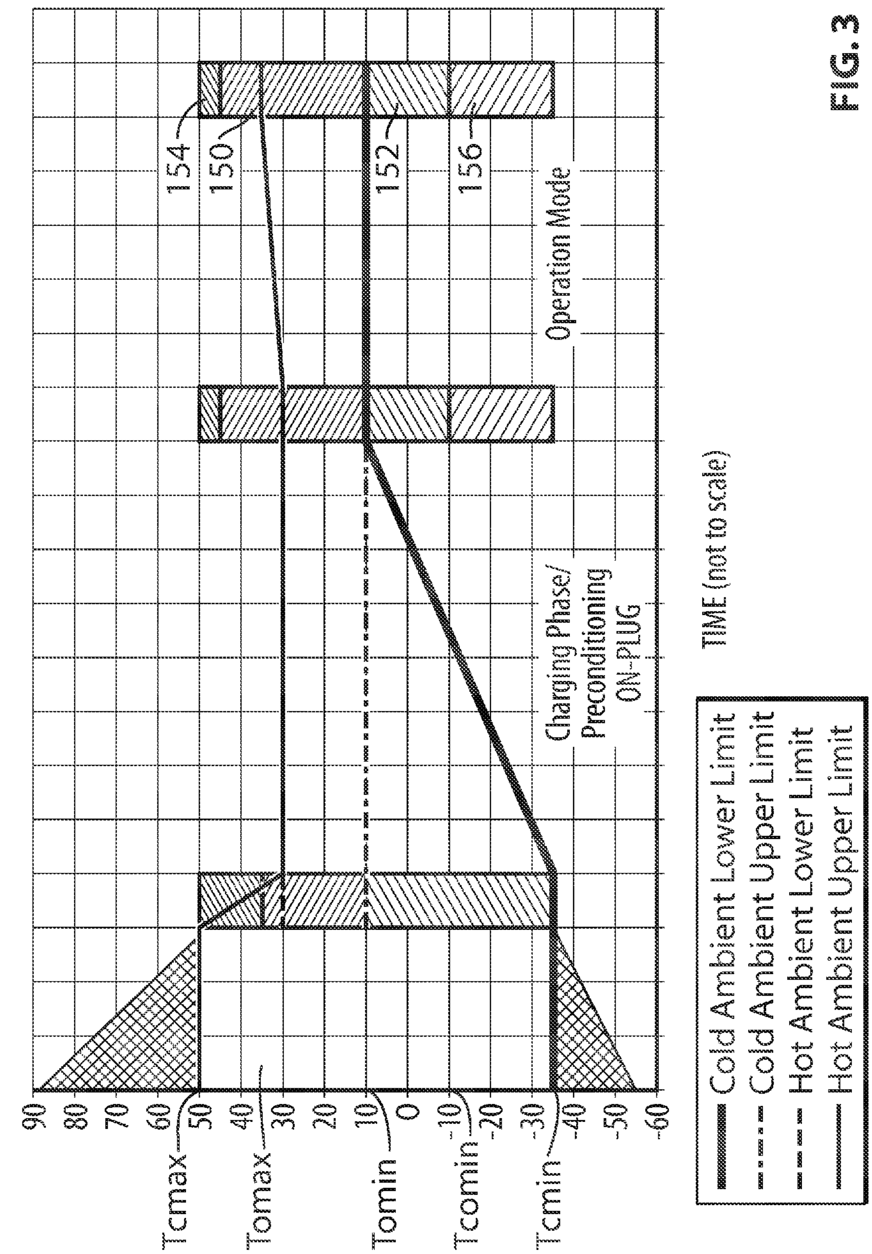

Tcmax
Tomax
Tomin
Tcomin
Tcmin
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
154
150
152
156
Charging Phase/
Preconditioning
ON-PLUG
Operation Mode
TIME (not to scale)
Cold Ambient Lower Limit
Cold Ambient Upper Limit
Hot Ambient Lower Limit
Hot Ambient Upper Limit

FIG. 3

THERMAL MANAGEMENT SYSTEM FOR BATTERY ELECTRIC VEHICLE

FIELD OF THE INVENTION

[0001] The present invention relates to electric vehicles (i.e., vehicles that are powered at least partly by an electric motor) and more particularly to battery electric vehicles with no internal combustion engine on board.

BACKGROUND OF THE INVENTION

[0002] Electric vehicles offer the promise of powered transportation through the use of electric motors while producing few or no emissions. Some electric vehicles are powered by electric motors only and rely solely on the energy stored in an on-board battery pack. Other electric vehicles are hybrids, and include an internal combustion engine, which may, for example, be used to assist the electric motor in driving the wheels (a parallel hybrid), or which may, for example, be used solely to charge the on-board battery pack, thereby extending the operating range of the vehicle (a series hybrid). In some vehicles, there is a single, centrally-positioned electric motor that powers one or more of the vehicle wheels, and in other vehicles, one or more of the wheels have an electric motor positioned at each driven wheel.

[0003] While currently proposed and existing vehicles are advantageous in some respects over internal-combustion engine powered vehicles, there are problems that are associated with some electric vehicles. A particular problem is that their range is typically relatively short as compared to internal combustion engine-powered vehicles. This is particularly true for battery electric vehicles that are not equipped with range extender engines. A reason for this limitation is the weight and cost of the battery packs used to store energy for the operation of such vehicles. It would be beneficial to provide technology that improves the efficiency with which power is used in the operation of the vehicle, so as to improve the range of such vehicles.

SUMMARY OF THE INVENTION

[0004] In a first aspect, the invention is directed to a thermal management system for an electric vehicle. The thermal management system includes a motor circuit for cooling a motor circuit thermal load and a second circuit, which may be, for example, a cabin heating circuit for heating a cabin heater or a battery circuit for managing the temperature of a battery circuit thermal load. The second circuit can be isolated from the motor circuit so that the fluid in the second circuit can be brought to a temperature that is different from the temperature of the fluid in the motor circuit. In a preferred embodiment, a single valve can be moved from a first position wherein fluid flow passes between two of the circuits to a second position wherein the two circuits are fluidically isolated from each other.

[0005] In a particular embodiment of the first aspect, the thermal management system includes a motor circuit, a cabin heating circuit for heating a passenger cabin, a motor circuit temperature sensor, and a controller. The motor circuit is configured for cooling a motor circuit thermal load including the traction motor. The motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet. The motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit. The cabin heating circuit is configured for heat exchange with a cabin heating circuit thermal load which includes a cabin heater for heating the cabin. The cabin heating circuit thermal load has a cabin heating circuit thermal load inlet and a cabin heating circuit thermal load outlet, a first cabin heating circuit conduit fluidically between the motor circuit and the cabin heating circuit thermal load inlet, a second cabin heating circuit conduit fluidically between the cabin heating circuit thermal load outlet and the motor circuit, a third cabin heating circuit conduit fluidically between the second and first cabin heating circuit conduits, a cabin heating circuit heater positioned to heat fluid in the cabin heating circuit, a cabin heating circuit valve positionable in a first position wherein fluid flow between the motor circuit and the cabin heating circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the cabin heating circuit is permitted, and a cabin heating circuit pump positioned to pump fluid through the cabin heating circuit. The motor circuit temperature sensor is positioned to detect the temperature of fluid in the second motor circuit conduit. The controller is operatively connected to the cabin heating circuit valve, the cabin heating circuit heater and to the cabin heating circuit pump. The controller is programmed such that when the cabin heating circuit thermal load requires heat and the temperature sensed by the motor circuit temperature sensor is sufficiently high the controller turns off the cabin heating circuit heater and moves the cabin heating circuit valve to the second position, and when the cabin heating circuit thermal load requires heat and the temperature sensed by the motor circuit temperature sensor is sufficiently low the controller turns on the cabin heating circuit heater, operates the cabin heating circuit pump and moves the cabin heating circuit valve to the first position.

[0006] In another particular embodiment of the first aspect, the thermal management system includes a motor circuit, a battery circuit for controlling the temperature of a battery circuit thermal load which includes at least one battery pack, a motor circuit temperature sensor, and a controller. The motor circuit is configured for cooling a motor circuit thermal load including the traction motor. The motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet. The motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit. The battery circuit is configured for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack. The battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet. The battery circuit includes a first battery circuit conduit fluidically between the motor circuit and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the motor circuit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a battery circuit heater positioned to heat fluid in the battery circuit, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit. The motor circuit temperature sensor is positioned to detect the temperature of fluid in the second motor circuit conduit. The controller is operatively connected to the battery circuit valve, the battery circuit heater and to the battery circuit pump. The controller is programmed such that when heating of the battery circuit thermal load is required and the temperature sensed by the motor circuit temperature sensor is sufficiently high the controller turns off the battery circuit heater and moves the battery circuit valve to the second position, and when heating of the battery circuit thermal load is required and the temperature sensed by the motor circuit temperature sensor is sufficiently low the controller turns on the battery circuit heater, operates the battery circuit pump and moves the battery circuit valve to the first position.

[0007] In a second aspect, the invention is directed to a thermal management system for an electric vehicle. The thermal management system includes a motor circuit for cooling a motor circuit thermal load, a cabin heating circuit for heating a cabin heater and a battery circuit for managing the temperature of a battery circuit thermal load. All of these circuits can fluidically communicate with each other and a single radiator can cool the fluid from all of these circuits. In a preferred embodiment, the system includes a main cooling circuit which includes a compressor and a condenser.

[0008] In a particular embodiment of the second aspect, the thermal management system includes a motor circuit, a cabin heating circuit for heating a passenger cabin, a battery circuit for controlling the temperature of a battery circuit thermal load which includes at least one battery pack, a motor circuit temperature sensor, and a controller. The motor circuit is configured for cooling a motor circuit thermal load including the traction motor. The motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet. The motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit. The cabin heating circuit is configured for heat exchange with a cabin heating circuit thermal load which includes a cabin heater for heating the cabin. The cabin heating circuit thermal load has a cabin heating circuit thermal load inlet and a cabin heating circuit thermal load outlet, a first cabin heating circuit conduit fluidically between the motor circuit and the cabin heating circuit thermal load inlet, a second cabin heating circuit conduit fluidically between the cabin heating circuit thermal load outlet and the motor circuit, a third cabin heating circuit conduit fluidically between the second and first cabin heating circuit conduits, a cabin heating circuit heater positioned to heat fluid in the cabin heating circuit, a cabin heating circuit valve positionable in a first position wherein fluid flow between the motor circuit and the cabin heating circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the cabin heating circuit is permitted, and a cabin heating circuit pump positioned to pump fluid through the cabin heating circuit. The motor circuit temperature sensor is positioned to detect the temperature of fluid in the second motor circuit conduit. The battery circuit is configured for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack. The battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet. The battery circuit includes a first battery circuit conduit fluidically between the motor circuit and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the motor circuit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a battery circuit heater positioned to heat fluid in the battery circuit, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit. The controller is operatively connected to the cabin heating circuit valve to control the flow of fluid between the motor circuit and the cabin heating circuit and operatively connected to the battery circuit valve to control the flow of fluid between the motor circuit and the battery circuit, such that heat transferred to fluid in the motor circuit by the motor circuit thermal load is removed from the fluid by at least one of the group selected from the cabin heating circuit thermal load, the battery circuit thermal load and the radiator.

[0009] In a third aspect, the invention is directed to a thermal management system for an electric vehicle. The electric vehicle includes a traction motor and at least one battery pack. The thermal management system is capable of heating the at least one battery pack using a low voltage heater.

[0010] The thermal management system includes a battery circuit that is configured for controlling the temperature of a battery circuit thermal load including the at least one the battery pack, and including a battery circuit thermal load inlet and a battery circuit thermal load outlet. The battery circuit includes a first battery circuit conduit extending to the battery circuit thermal load inlet, a second battery circuit conduit from the battery circuit thermal load outlet, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, and a battery circuit pump in the first battery circuit conduit configured to pump fluid through the battery circuit. The thermal management system includes a battery charge control module. When the vehicle is plugged into an electrical source the battery charge control module receives energy from the electrical source and processes the energy for storage in the at least one battery pack. When the at least one battery pack is below a selected battery pack temperature and the vehicle is plugged into an electrical source the controller is programmed to position the battery circuit valve in the second position wherein heat generated in the battery charge control module heats fluid passing through therethrough. The fluid is circulated to the at least one battery pack to heat the at least one battery pack. A battery circuit heater is positioned to heat fluid in the battery circuit. The battery circuit heater is configured to operate with an inlet voltage of 12VDC.

[0011] In a fourth aspect, the invention is directed to a thermal management system for an electric vehicle. The electric vehicle includes a traction motor and at least one battery pack. The thermal management system includes a motor circuit a battery circuit, a main cooling circuit, a motor circuit temperature sensor and a controller. The motor circuit is configured for cooling a motor circuit thermal load including the traction motor. The motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet. The motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit. The battery circuit is configured for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack. The battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet. The battery circuit includes a first battery circuit conduit fluidically between the second motor circuit conduit upstream from the radiator and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the first motor circuit conduit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a chiller positioned to cool fluid in the battery circuit, the chiller having a refrigerant inlet and a refrigerant outlet, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit. The main cooling circuit includes a compressor, a first cooling circuit conduit positioned upstream of the compressor and positioned for receiving refrigerant from the refrigerant outlet of the evaporator and for receiving refrigerant from the refrigerant outlet of the chiller, a condenser positioned downstream from the compressor, a second cooling circuit conduit positioned downstream of the condenser and positioned for delivering refrigerant to the refrigerant inlet of the chiller and to the refrigerant inlet of the evaporator and a chiller refrigerant flow control valve positioned for controlling the flow of refrigerant through the chiller. The motor circuit temperature sensor is positioned to detect the temperature of fluid in the second motor circuit conduit. The controller is operatively connected to the chiller refrigerant flow control valve, the evaporator refrigerant flow control valve, the battery circuit valve, the battery circuit pump and the compressor. The controller is programmed to open the chiller refrigerant flow control valve based on a comparison of the temperature sensed by the motor circuit temperature sensor and a target temperature for the battery circuit thermal load, and to open the evaporator refrigerant flow control valve based on a temperature setting of a climate control system for the passenger cabin.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The present invention will now be described, by way of example only, with reference to the attached drawings, in which:

[0013] FIG. **1** is a perspective view of an electric vehicle that includes a thermal management system in accordance with an embodiment of the present invention;

[0014] FIG. **2** is a schematic illustration of a thermal management system for the electric vehicle; and

[0015] FIG. **3** is a graph of the temperature of battery packs that are part of the electric vehicle shown in FIG. **1**.

DETAILED DESCRIPTION OF THE INVENTION

[0016] Reference is made to FIG. **2**, which shows a schematic illustration of a thermal management system **10** for an electric vehicle **12** shown in FIG. **1**. The electric vehicle **12** includes wheels **13**, a traction motor **14** for driving the wheels **13**, first and second battery packs **16***a* and **16***b*, a cabin **18**, a high voltage electrical system **20** (FIG. **2**) and a low voltage electrical system **22** (FIG. **2**).

[0017] The motor **14** may have any suitable configuration for use in powering the electric vehicle **12**. The motor **14** may be mounted in a motor compartment that is forward of the cabin **18** and that is generally in the same place an engine compartment is on a typical internal combustion powered vehicle. Referring to FIG. **2**, the motor **14** generates heat during use and thus requires cooling. To this end, the motor **14** includes a motor coolant flow conduit for transporting coolant fluid about the motor **14** so as to maintain the motor within a suitable temperature range.

[0018] A transmission control system shown at **28** is part of the high voltage electrical system **20** and is provided for controlling the current flow to high voltage electrical loads within the vehicle **12**, such as the motor **14**, an air conditioning compressor **30**, a heater **32** and a DC/DC converter **34**. The transmission control system **28** generates heat during use and thus has a transmission control system coolant flow conduit associated therewith, for transporting coolant fluid about the transmission control system **28** so as to maintain the transmission control system **28** within a suitable temperature range. The transmission control system **28** may be positioned immediately upstream fluidically from the motor **14**.

[0019] The DC/DC converter **34** receives current from the transmission control system **28** and converts it from high voltage to low voltage. The DC/DC converter **34** sends the low voltage current to a low voltage battery shown at **40**, which is used to power low voltage loads in the vehicle **12**. The low voltage battery **40** may operate on any suitable voltage, such as 12 V.

[0020] The battery packs **16***a* and **16***b* send power to the transmission control system **28** for use by the motor **14** and other high voltage loads and thus form part of the high voltage electrical system **20**. The battery packs **16***a* and **16***b* may be any suitable types of battery packs. In an embodiment, the battery packs **16***a* and **16***b* are each made up of a plurality of lithium polymer cells. The battery packs **16***a* and **16***b* have a temperature range (shown in FIG. **3**) in which they are preferably maintained so as to provide them with a relatively long operating life. While two battery packs **16***a* and **16***b* are shown, it is alternatively possible to have any suitable number of battery packs, such as one battery pack, or 3 or more battery packs depending on the packaging constraints of the vehicle **12**.

[0021] A battery charge control module shown at **42** is provided and is configured to connect the vehicle **12** to an electrical source (such as, for example, a 110V source, or a 220V source) shown at **44**, and to send the current received from the electrical source **44** to any of several destinations, such as, the battery packs **16***a* and **16***b*, the transmission control system **28** and the low voltage battery **40**. The battery charge control module **42** generates heat during use and thus requires cooling. To this end, the battery charge control module **42** includes a battery charge control module fluid flow conduit for transporting fluid about the battery charge control module **42** from a battery charge control module inlet **4** to a battery charge control module outlet **26** so as to maintain the battery charge control module **42** within a suitable temperature range.

[0022] An HVAC system **46** is provided for controlling the temperature of the cabin **18** (FIG. **1**). The HVAC system **46** is configured to be capable of both cooling and heating the cabin **18**. To achieve this, the HVAC system **46** may include one or more heat exchangers, such as a cabin heating heat exchanger **47** and a cabin cooling heat exchanger **48** (which may be referred to as evaporator **48**). The cabin heating heat exchanger **47** has a heat exchange fluid inlet **49** and a heat exchange fluid outlet **50** and is used to heat an air flow that is passed into the cabin **18**. The cabin cooling heat exchanger **48** includes a refrigerant inlet **51** and a refrigerant outlet **52**, and is used to cool an air flow that is passed into the cabin **18**.

[0023] The motor **14**, the transmission control system **28**, the DC/DC converter **34**, the battery packs **16***a* and **16***b*, the battery charge control module **42** and the HVAC system **46** constitute thermal loads on the thermal management system **10**.

[0024] The thermal management system **10** includes a motor circuit **56**, a cabin heating circuit **58**, a battery circuit **60** and a main cooling circuit **62**. The motor circuit **56** is configured for cooling the traction motor **14**, the transmission control system **28** and the DC/DC converter **34**, which constitute a motor circuit thermal load **61**, which has a motor circuit thermal load inlet **63** and a motor circuit thermal load outlet **65**. The motor circuit **56** includes a radiator **64**, a first motor circuit conduit **66** fluidically between the radiator **64** to the motor circuit thermal load inlet **63**, a second motor circuit conduit **68** fluidically between the motor circuit thermal load outlet **65** and the radiator **64**, and a motor circuit pump **70** positioned to pump heat exchange fluid through the motor circuit **56**.

[0025] Additionally a third motor circuit conduit **74** may be provided fluidically between the second and first motor circuit conduits **68** and **66** so as to permit the flow of heat exchange fluid to bypass the radiator **64** when possible (for example, when the heat exchange fluid is below a selected threshold temperature). To control whether the flow of heat exchange fluid is directed through the radiator **64** or through the third motor circuit conduit **74**, a radiator bypass valve **75** is provided and may be positioned in the second motor circuit conduit **68**. The radiator bypass valve **75** is controllable so that in a first position it directs the flow of heat exchange fluid to the radiator **64** through the second motor circuit conduit **68** and in a second position it directs the flow of heat exchange fluid to the first motor circuit conduit **66** through the third motor circuit conduit **74**, so as to bypass the radiator **64**. Flow through the third motor circuit conduit **74** is easier than flow through the radiator **64** (in other words, there is less of a pressure drop associated with flow through the third conduit than there is with flow through the radiator **64**) and so bypassing the radiator **64** whenever possible, reduces the energy consumption of the pump **70**. By reducing the energy consumed by components in the vehicle **12** (FIG. **1**), the range of the vehicle can be extended, which is particularly advantageous in electric vehicles.

[0026] It will be noted that only a single radiator bypass valve **75** is provided for bypassing the radiator **64**. When the radiator bypass valve **75** is in the first position, all of the heat exchange fluid flow is directed through the second conduit **68**, through the radiator **64** and through the first conduit **66**. There is no net flow through the third conduit **74** because there is no net flow into the third conduit. Conversely, when the radiator bypass valve **75** is in the second position, all of the heat exchange fluid flow is directed through the third conduit **74** and back to the first conduit **66**. There is no net flow through the radiator **64** because there is no net flow into the radiator **64**. Thus, using only a single valve (such as the bypass valve **75**) provides the capability of selectably bypassing the radiator **64**, instead of using one valve at the junction of the second and third conduits **68** and **74** and another valve at the junction of the first and third conduits **66** and **74**. As a result of using one valve (such as valve **75**) instead of two valves, the motor circuit **56** contains fewer components, thereby making it less expensive, simpler to make and to operate and more reliable. Furthermore by eliminating one valve, the energy required to move the heat exchange fluid through the motor circuit **56** is reduced, thereby reducing the energy consumed by the pump **70** and extending the range of the vehicle **12** (FIG. **1**).

[0027] The pump **70** may be positioned anywhere suitable, such as in the first motor circuit conduit **66**.

[0028] The elements that make up the motor circuit thermal load may be arranged in any suitable way. For example, the DC/DC converter **34** may be downstream from the pump **70** and upstream from the transmission control system **28**, and the motor **14** may be downstream from the transmission control system **28**. Thus, the inlet to the DC/DC converter **34** constitutes the thermal load inlet **63** and the motor outlet constitutes the thermal load outlet **65**.

[0029] A motor circuit temperature sensor **76** is provided for determining the temperature of heat exchange fluid at a selected point in the motor circuit **56**. As an example, the motor circuit temperature sensor **76** may be positioned downstream from all the thermal loads in the motor circuit **56**, so as to record the highest temperature of the heat exchange fluid. Based on this temperature, a controller, shown at **78**, can determine whether or not to position the radiator bypass valve **75** in a first position wherein the radiator bypass valve **75** transfers the flow of heat exchange fluid towards the radiator **64** and a second position wherein the radiator bypass valve **75** bypasses the radiator **64** and transfers the flow of heat exchange fluid through the third motor circuit conduit **74** back to the first motor circuit conduit **66**.

[0030] The cabin heating circuit **58** is configured for providing heated heat exchange fluid to the HVAC system **46** and more specifically to the cabin heating heat exchanger **47**, which constitutes the cabin heating circuit thermal load. The cabin heating circuit **58** includes a first cabin heating circuit conduit **80** fluidically between the second motor circuit conduit **68** and the cabin heating heat exchanger inlet **49** (which in the embodiment shown is the inlet to the cabin heating circuit thermal load), a second cabin heating circuit conduit **82** fluidically between the cabin heating circuit heat exchanger outlet **50** (which in the embodiment shown is the outlet from the cabin heating circuit thermal load) to the motor circuit **56**. In the embodiment shown the second cabin heating circuit conduit **82** extends to the third motor circuit conduit **74**. This is because the cabin heating heat exchanger **47** serves to cool the heat exchange fluid by some amount, so that the resulting cooled heat exchange fluid need not be passed through the radiator **64** in the motor circuit **56**. By reducing the volume of heat exchange fluid that passes through the radiator **64**, energy consumed by the pump **70** is reduced, thereby extending the range of the vehicle **12** (FIG. **1**). It will be understood that in an alternative, less-preferred embodiment however, the second cabin heating circuit conduit **82** may extend to the second motor circuit conduit **68** downstream so that the heat exchange fluid contained in the second cabin heating circuit conduit **82** passes through the radiator **64**.

[0031] In some situations the heat exchange fluid will not be sufficiently hot to meet the demands of the HVAC system **46**. For such situations, the heater **32** which may be referred to as the cabin heating circuit heater **32** is provided in the first cabin heating circuit conduit **80**. The cabin heating circuit heater **32** may be any suitable type of heater, such as an electric heater that is one of the high voltage electrical components fed by the transmission control system **28**.

[0032] A third cabin heating circuit conduit **84** may be provided between the second and first cabin heating circuit conduits **82** and **80**. A cabin heating circuit pump **86** is provided in the third conduit **84**. In some situations it will be desirable to circulate heat exchange fluid through the cabin heating circuit **58** and not to transfer the fluid back to the motor circuit **56**. For example, when the fluid is being heated by the heater **32** it may be advantageous to not transfer the fluid back to the motor circuit **56** since the fluid in the motor circuit **56** is used solely for cooling the thermal load **61** and it is thus undesirable to introduce hot fluid into such a circuit. For the purpose of preventing fluid from being transferred from the cabin heating circuit **58** back to the motor circuit **56**, a cabin heating circuit valve **88** is provided. In the embodiment shown, the cabin heating circuit valve **88** is positioned in the second motor circuit conduit **68** and is positionable in a first position wherein the valve **88** directs fluid flow towards the radiator **64** through the second motor circuit conduit **68**, and a second position wherein the valve **88** directs fluid flow towards the cabin heater heat exchanger **47** through the first cabin heating circuit conduit **80**.

[0033] When the cabin heating circuit valve **88** is in the second position, the pump **86** may operate at a selected, low, flow rate to prevent the fluid flow from short circuiting the cabin heating circuit by flowing up the third conduit **84**.

[0034] It will be noted that separation of the fluid flow through the cabin heating circuit **58** and the motor circuit **56** is achieved using a single valve (such as valve **88**) which is positioned at the junction of the second motor circuit conduit **68** and the first cabin heating circuit conduit **80**. When the valve **88** is positioned in the first position, fluid is directed towards the radiator **64**. There is no net flow out of the cabin heating circuit **58** since there is no flow into the cabin heating circuit **58**. When the valve **88** is positioned in the second position and the pump **86** is off; fluid is directed through the cabin heating circuit **58** and back into the motor circuit **56**. When the valve **88** is positioned in the first position and the pump **86** is on, there is no net flow out of the second cabin heating circuit conduit **82** as noted above, however, the pump **86** generates a fluid circuit loop and drives fluid in a downstream portion **90** of the first cabin heating circuit conduit **80**, through the cabin heating heat exchanger **47**, and through an upstream portion **92** of the second cabin heating circuit conduit **82**, whereupon the fluid is drawn back into the pump **86**. Because this feature is provided using a single valve (such as valve **88**), as opposed to using one valve at the junction of the first cabin heating circuit conduit **80** and the motor circuit **56** and another valve at the junction of the second cabin heating circuit conduit **82** and the motor circuit **56**, the thermal management system **10** is made simpler and less expensive, and it further saves energy consumption by having fewer valves in the system **10** so as to reduce the energy required by the pump **70** to pump liquid through such valves.

[0035] Additionally, the valve **88** combined with the pump **86** permit isolating heated fluid in the cabin heating circuit **58** from the fluid in the motor circuit **56**, thereby preventing fluid that has been heated in the cabin heating circuit heater **32** from being sent to the radiator **64** to be cooled.

[0036] A cabin heating circuit temperature sensor **94** may be provided for determining the temperature of the fluid in the cabin heating circuit **58**. The temperature sensor **94** may be positioned anywhere suitable, such as downstream from the cabin heating circuit heater **32**. The temperature sensor **94** may communicate with the controller **78** so that the controller **78** can determine whether or not to carry out certain actions. For example, using the temperature sensed by the temperature sensor **94**, the controller **78** can determine whether the heater **32** should be activated to meet the cabin heating demands of the HVAC system **46**.

[0037] The battery circuit **60** is configured for controlling the temperature of the battery packs **16*a*** and **16*b*** and the battery charge control module **42**, which together make up the battery circuit thermal load **96**. A thermal load inlet is shown at **98** upstream from the battery packs **16*a*** and **16*b*** and a thermal load outlet is shown at **100** downstream from the battery charge control module **42**. The battery packs **16*a*** and **16*b*** are in parallel in the battery circuit **60**, which permits the fluid flow to each of the battery packs **16*a*** and **16*b*** to be selected individually so that each battery pack **16*a*** or **16*b*** receives as much fluid as necessary to achieve a selected temperature change. It may be possible to provide a means for adjusting the flow of fluid that goes to each battery pack **16*a*** and **16*b*** during use of the thermal management system **10**, so that the fluid flow can be adjusted to meet the instantaneous demands of the battery packs **16*a*** and **16*b***. After the fluid has passed through the battery packs **16*a*** and **16*b***, the fluid is brought into a single conduit which passes through the battery charge control module **42**. While the battery packs **16*a*** and **16*b*** are shown in parallel in the battery circuit **60**, they could be provided in series in an alternative embodiment.

[0038] A first battery circuit conduit **102** extends between the second motor circuit conduit **68** and the battery circuit thermal load inlet **98**. A second battery circuit conduit **104** extends between the thermal load outlet **100** and the first motor circuit conduit **66**. A battery circuit pump **106** may be provided for pumping fluid through the battery circuit **60** in situations where the battery circuit **60** is isolated from the motor circuit **56**. A battery circuit heater **108** is provided in the first conduit **102** for heating fluid upstream from the thermal load **96** in situations where the thermal load **96** requires it. The battery circuit heater **108** may operate on current from a low voltage current source, such as the low voltage battery **40**. This is discussed in further detail further below.

[0039] A third battery circuit conduit **110** may be provided fluidically between the second and first battery circuit conduits **102** and **104** so as to permit the flow of heat exchange fluid in the battery circuit **60** to be isolated from the flow of heat exchange fluid in the motor circuit **56**. A chiller **112** may be provided in the third conduit **110** for cooling fluid upstream from the thermal load **96** when needed.

[0040] A battery circuit valve **114** is provided in the second conduit **104** and is positionable in a first position wherein the flow of fluid is directed towards the first motor circuit conduit **66** and in a second position wherein the flow of fluid is directed into the third battery circuit conduit **114** towards the first battery circuit conduit **102**.

[0041] It will be noted that the flow in the battery circuit **60** is isolated from the flow in the motor circuit **56** with only one valve (such as valve **114**). When the valve **114** is in the second position so as to direct fluid flow through the third conduit **110** into the first conduit **102**, there is effectively no flow from the first motor circuit **56** through the first conduit **102** since the loop made up of the downstream portion of the first conduit **102**, the thermal load **96**, the second conduit **104** and the third conduit **110** is already full of fluid. By using only one valve (such as valve **114**) to isolate the battery circuit **60**, the amount of energy consumed by the pump **106** to pump fluid around the battery circuit **60** is reduced relative to a similar arrangement using two valves. Additionally, by using only one valve the battery circuit is simpler (i.e., it has fewer components), which reduces its cost and which could increase its reliability.

[0042] A battery circuit temperature sensor **116** is provided for sensing the temperature of the fluid in the battery circuit **60**. The temperature sensor **116** may be positioned anywhere in the battery circuit **60**, such as in the second conduit **104** downstream from the thermal load **96**. The temperature from the temperature sensor **116** can be sent to the controller **78** to determine whether to have the valve **114** should be in the first or second position and whether any devices (such as, for example, the chiller **112**, the heater **108**) need to be operated to adjust the temperature of the fluid in the first conduit **102**.

[0043] The main cooling circuit **62** is provided for assisting in the thermal management of the thermal loads in the HVAC system **46** and the battery circuit **60**. More particularly, the thermal load in the HVAC system **46** is shown at **118** and is made up of the cabin cooling heat exchanger **48** (i.e., the evaporator **48**).

[0044] The components of the main cooling circuit **62** that are involved in the cooling and management of the refrigerant flowing therein include the compressor **30** and a condenser **122**. A first cooling circuit conduit **126** extends from the condenser **122** to a point wherein the conduit **126** divides into a first branch **128** which leads to the HVAC system **46** and a second branch **130** which leads to the battery circuit **60**. A second cooling circuit conduit **132** has a first branch **134** that extends from the HVAC system **46** to a joining point and a second branch **136** that extends from the battery circuit **60** to the joining point. From the joining point, the second cooling circuit conduit **132** extends to the inlet to the compressor **30**.

[0045] At the downstream end of the first branch **128** of the first conduit **126** is a flow control valve **138** which controls the flow of refrigerant into the cabin cooling heat exchanger **48**. The upstream end of the first branch **134** of the second conduit **132** is connected to the refrigerant outlet from the heat exchanger **48**. It will be understood that the valve **138** could be positioned at the upstream end of the first branch **134** of the second conduit **132** instead. The valve **138** is controlled by the controller **78** and is opened when refrigerant flow is needed through the heat exchanger **48**.

[0046] At the downstream end of the second branch **130** of the first conduit **126** is a flow control valve **140** which controls the flow of refrigerant into the battery circuit chiller **112**. The upstream end of the second branch **136** of the second conduit **132** is connected to the refrigerant outlet from the chiller **112**. It will be understood that the valve **140** could be positioned at the upstream end of the second branch **136** of the second conduit **132** instead. The valve **140** is controlled by the controller **78** and is opened when refrigerant flow is needed through the chiller **112**.

[0047] The valves **138** and **140** may be any suitable type of valves with any suitable type of actuator. For example, they may be solenoid actuated/spring return valves. Additionally thermostatic expansion valves shown at **139** and **141** may be provided downstream from the valves **138** and **140**.

[0048] A refrigerant pressure sensor **142** may be provided anywhere suitable in the cooling circuit **62**, such as on the first conduit **126** upstream from where it divides into the first and second branches **128** and **130**. The pressure sensor **142** communicates pressure information from the cooling circuit **62** to the controller **78**.

[0049] A fan shown at **144** is provided for blowing air on the radiator **64** and the condenser **122** to assist in cooling and condensing the heat exchange fluid and the refrigerant respectively. The fan **144** is controlled by the controller **78**.

[0050] An expansion tank **124** is provided for removing gas that can accumulate in other components such as the radiator **64**. The expansion tank **124** is preferably positioned at the highest elevation of any fluid-carrying components of the thermal management system. The expansion tank **124** may be used as a point of entry for heat exchange fluid into the thermal management system **10** (i.e., the system **10** may be filled with the fluid via the expansion tank **124**).

[0051] The controller **78** is described functionally as a single unit, however the controller **78** may be made up of a plurality of units that communicate with each other and which each control one or more components of the thermal management system **10**, as well as other components optionally.

[0052] The logic used by the controller **78** to control the operation of the thermal management system **10** depends on which of several states the vehicle is in. The vehicle may be on-plug and off, which means that the vehicle itself is off (for example, the ignition key is out of its slot in the instrument panel) and is plugged into an external electrical source (for example, for recharging the battery packs **16**_a_ and **16**_b_). The vehicle may be off-plug and off, which means that the vehicle itself is off and is not plugged into an external electrical source. The vehicle may be off-plug and on, which means that the vehicle itself is on and is not plugged into an external electrical source. The logic used by the controller **78** may be as follows:

[0053] The controller **78** attends to the cooling requirements of the thermal load **61** of the motor circuit **56** when the vehicle is off-plug and when the vehicle is on. The controller **78** determines a maximum permissible temperature for the heat exchange fluid and determines if the actual temperature of the heat exchange fluid exceeds it (based on the temperature sensed by the temperature sensor **76**) by more than a selected amount (which is a calibrated value, and which could be zero for example). If so, the controller operates the pump **70** to circulate the heat exchange fluid through the motor circuit **56**. Initially when the vehicle enters the state of being off-plug and on, the controller **78** may default to a ‘cooling off’ mode wherein the pump **70** is not turned on, until it has determined and compared the aforementioned temperature values. In the event that the vehicle is in a fault state, the controller **78** may enter a motor circuit cooling fault mode. When the controller **78** exits the fault state, the controller **78** may pass to the ‘cooling off’ mode.

[0054] The controller **78** attends to the heating and cooling requirements of the cabin heating circuit **58** when the vehicle is on-plug and when the vehicle is off-plug and on. The controller **78** may have three cabin heating modes. The controller **78** determines if the requested cabin temperature from the climate control system in the cabin **18** exceeds the temperature sensed by a temperature sensor in the evaporator **48** that senses the actual temperature in the cabin **18** by a selected calibrated amount. If so, and if the vehicle is either off plug and on or on plug and there is sufficient power available from the electrical source, and if the controller **78** determines if the temperature sensed by the temperature sensor **76** is higher than the requested cabin temperature by a selected calibrated amount. If it is higher, then the controller **78** positions the cabin heating circuit valve **88** in its second position wherein flow is generated through the cabin heating circuit **58** from the motor circuit **56** and the controller **78** puts the cabin heating circuit heater **32** in the off position. These settings make up the first cabin heating mode. If the temperature sensed by the temperature sensor **76** is lower than the requested cabin temperature by a selected calibrated amount, then the controller **78** positions the cabin heating circuit valve **88** in the first position and turns on the pump **86** so that flow in the cabin heating circuit **58** is isolated from flow in the motor circuit **56**, and the controller **78** additionally turns on the cabin heating circuit heater **32** to heat the flow in the cabin heating circuit **58**. These settings make up the second cabin heating mode.

[0055] If the temperature sensed by the temperature sensor **76** is within a selected range of the requested temperature from the climate control system then the controller **78** positions the cabin heating circuit valve **88** in the second position so that flow in the cabin heating circuit **58** is not isolated from flow in the motor circuit **56**, and the controller turns the heater **32** on. These settings make up the third cabin heating mode. The selected range may be the requested temperature from the climate control system minus the selected calibrated value, to the requested temperature from the climate control system plus the selected calibrated value.

[0056] The default state for the controller **78** when cabin heating is initially requested may be to use the first cabin heating mode.

[0057] The controller **78** may have one cabin cooling mode. The controller **78** determines if the actual temperature of the evaporator **48** is lower than the target temperature of the evaporator **48** by more than a calibrated amount. If so, and if the vehicle is either off plug and on or on plug and there is sufficient power available from the electrical source, then the controller **78** turns on the compressor **30** and moves the refrigerant flow control valve **138** to the open position so that refrigerant flows through the cabin cooling heat exchanger **48** to cool an air flow that is passed into the cabin **18**.

[0058] The thermal management system **10** will enter a cabin heating and cabin cooling fault mode when the vehicle is in a fault state.

[0059] When the climate control system in the cabin **18** is set to a ‘defrost’ setting, the controller **78** will enter a defrost mode, and will return to whichever heating or cooling mode it was in once defrost is no longer needed.

[0060] The default mode for the controller **78** with respect to the cabin heating circuit **58** may be to have the cabin heating circuit valve **88** in the first position to direct flow towards the radiator, and to have the heater **32** off, the pump **86** off. The default mode for the controller **78** with respect to cooling the cabin **18** may to be to have the refrigerant flow control valve **138** in the closed position to prevent refrigerant flow through the cabin cooling heat exchanger **48**, and to have the compressor **30** off.

[0061] The controller **78** attends to the heating and cooling requirements of the battery circuit **60** when the vehicle is on-plug and is off, and when the vehicle is off-plug and is on. The controller **78** may have three cooling modes for cooling the battery circuit thermal load **96**. The controller **78** determines a desired battery pack temperature based on the particular situation, and determines if a first cooling condition is met, which is whether the desired battery pack temperature is lower than the actual battery pack temperature by a first selected calibrated amount. If the first cooling condition is met, the controller **78** determines which of the three cooling modes it will operate in by determining which, if any, of the following second and third cooling conditions are met. The second condition is whether the temperature sensed by the temperature sensor **76** is lower than the desired battery pack temperature by a second selected calibrated amount, which may, for example, be related to the expected temperature rise that would be incurred in the flow of fluid from the temperature sensor **76** to the battery circuit thermal load **96**. If the second condition is met, then the controller **78** operates in a first battery circuit cooling mode, wherein it positions the battery circuit valve **114** in its second position wherein flow is generated through the battery circuit **60** from the motor circuit **56** and the controller **78** puts the refrigerant flow control valve **140** in the closed position preventing refrigerant flow through the chiller **112**.

[0062] The third cooling condition is whether the temperature sensed by the temperature sensor **76** is greater than the desired battery pack temperature by at least a third selected calibrated amount, which may, for example, be related to the expected temperature drop associated with the chiller **112**. If the third cooling condition is met, then the controller **78** operates in a second battery circuit cooling mode wherein it positions the battery circuit valve **114** in the first position and turns on the pump **106** so that flow in the battery circuit **60** is isolated from flow in the motor circuit **56**, and the controller **78** additionally positions the flow control valve **140** in the open position so that refrigerant flows through the chiller **112** to cool the flow in the battery circuit **60**.

[0063] If neither the second or third cooling conditions are met (i.e., if the temperature sensed by the temperature sensor **76** is greater than or equal to the desired battery pack temperature minus the second selected calibrated amount and the temperature sensed by the temperature sensor **76** is less than or equal to the desired battery pack temperature plus the third selected calibrated amount), then the controller **78** operates in a third battery circuit cooling mode wherein it positions the battery circuit valve **114** in the second position so that flow in the battery circuit **60** is not isolated from flow in the motor circuit **56**, and the controller **78** turns the chiller **112** on.

[0064] It will be understood that in any of the battery circuit cooling modes, the controller **78** turns the battery circuit heater **108** off.

[0065] The default state for the controller **78** when battery circuit thermal load cooling is initially requested may be to use the first battery circuit cooling mode.

[0066] The controller **78** may have three battery circuit heating modes. The controller **78** determines a desired battery circuit thermal load temperature based on the particular situation, and determines whether a first heating condition is met, which is whether the desired battery pack temperature is higher than the actual battery pack temperature by a first selected calibrated amount. If the first heating condition is met, the controller **78** determines which of the three heating modes it will operate in by determining which, if any, of the following second and third heating conditions are met. The second heating condition is whether the temperature sensed by the temperature sensor **76** is higher than the desired battery pack temperature by a second selected calibrated amount that may, for example, be related to the expected temperature drop of the fluid as it flows from the temperature sensor **76** to the battery circuit thermal load **96**. If the second condition is met, then the controller **78** operates in a first battery circuit heating mode, wherein it positions the battery circuit valve **114** in its second position wherein flow is generated through the battery circuit **60** from the motor circuit **56** and the controller **78** turns the battery circuit heater **32** off.

[0067] The third heating condition is whether the temperature sensed by the temperature sensor **76** is lower than the desired battery pack temperature by at least a third selected calibrated amount, which may, for example, be related to the expected temperature rise associated with the battery circuit heater **108**. If this third heating condition is met, then the controller **78** operates in a second battery circuit heating mode wherein it positions the battery circuit valve **114** in the first position and turns on the pump **106** so that flow in the battery circuit **60** is isolated from flow in the motor circuit **56**, and the controller **78** additionally turns on the battery circuit heater **108** to heat the flow in the battery circuit **60**.

[0068] If neither the second or third conditions are met (i.e., if the temperature sensed by the temperature sensor **76** is less than or equal to the desired battery pack temperature plus the second selected calibrated amount and the temperature sensed by the temperature sensor **76** is greater than or equal to the desired battery pack temperature minus the third selected calibrated amount), then the controller **78** operates in a third battery circuit heating mode wherein it positions the battery circuit valve **114** in the second position so that flow in the battery circuit **60** is not isolated from flow in the motor circuit **56**, and the controller **78** turns the battery circuit heater **108** on.

[0069] The default state for the controller **78** when battery circuit thermal load heating is initially requested may be to use the first battery circuit heating mode.

[0070] The thermal management system **10** will enter a battery circuit heating and cooling fault mode when the vehicle is in a fault state.

[0071] When the vehicle is off-plug, the controller **78** heats the battery circuit thermal load **96** using only the first battery circuit heating mode.

[0072] The default state for the controller **78** when the vehicle is turned on is to position the battery circuit valve **114** in the first position so as to not generate fluid flow through the battery circuit **60**.

[0073] The controller **78** may operate using several other rules in addition to the above. For example the controller **78** may position the radiator bypass valve **75** in the first position to direct fluid flow through the radiator **64** if the temperature of the fluid sensed at sensor **76** is greater than the maximum acceptable temperature for the fluid plus a selected calibrated value and the cabin heating circuit valve **88** is in the first position and the battery circuit valve **114** is in the first position.

[0074] The controller **78** may also position the radiator bypass valve **75** in the first position to direct fluid flow through the radiator **64** if the temperature of the fluid sensed at sensor **76** has risen to be close to the maximum acceptable temperature for the fluid plus a selected calibrated value and the cabin heating circuit valve **88** is in the second position and the battery circuit valve **114** is in the second position.

[0075] In the event of an emergency battery shutdown, the controller **78** will shut off the compressor **30** and will turn on the cabin heating circuit heater **32** so as to bleed any residual voltage.

[0076] The temperature of the battery packs **16***a* and **16***b* may be maintained above their minimum required temperatures by the controller **78** through control of the refrigerant flow control valve **140** to the chiller **112**. The temperature of the evaporator may be maintained above a selected temperature which is a target temperature minus a calibrated value, through opening and closing of the refrigerant flow control valve **138**. The speed of the compressor **30** will be adjusted based on the state of the flow control valve **140** and of the flow control valve **138**.

[0077] The controller **78** is programmed with the following high level objectives and strategies using the above described modes. The high level objectives include:

[0078] A. control the components related to heating and cooling of the battery circuit thermal load **96** to maintain the battery packs **16***a* and **16***b* and the battery charge control module **42** within the optimum temperature range during charging and vehicle operation;

[0079] B, maintain the motor **14**, the transmission control system **28** and the DC/DC converter **34** at their optimum temperature ranges;

[0080] C. control the components related to heating and cooling the cabin **18** based on input from the climate control system; and

[0081] D. operate with a goal of maximizing vehicle range while meeting vehicle system requirements.

[0082] The controller **78** uses the following high level strategy on-plug:

[0083] When the vehicle is on-plug and is off, the controller **78** pre-conditions the battery packs **16***a* and **16***b* if required. Pre-conditioning entails bringing the battery packs **16***a* and **16***b* into a temperature range wherein the battery packs **16***a* and **16***b* are able to charge more quickly.

[0084] The controller **78** determines the amount of power available from the electrical source for temperature control of the battery packs **16***a* and **16***b*, which is used to determine the maximum permitted compressor speed, maximum fan speed or the battery pack heating requirements depending on whether the battery packs **16***a* and **16***b* require cooling or heating. A calibratible hysteresis band will enable the battery pack temperature control to occur in a cyclic manner if the battery pack temperatures go outside of the selected limits (which are shown in FIG. **3**). If sufficient power is available from the electrical source, the battery packs **16***a* and **16***b* may be charged while simultaneously being conditioned (i.e., while simultaneously being cooled or heated to remain within their selected temperature range). If the battery packs **16***a* and **16***b* reach their fully charged state, battery pack conditioning may continue, so as to bring the battery packs **16***a* and **16***b* to their selected temperature range for efficient operation.

[0085] When the vehicle is on-plug the battery circuit heater **108** may be used to bring the battery packs **16***a* and **16***b* up to a selected temperature range, as noted above. In one of the heating modes described above for the battery circuit **60**, the battery circuit valve **114** is in the second position so that the flow in the battery circuit **60** is isolated from the flow in the motor circuit **56**, and therefore the battery circuit heater **108** only has to heat the fluid in the battery circuit **60**.

[0086] The cabin may be pre-conditioned (such as, for example, heated or cooled while the vehicle is off) when the vehicle is on-plug and the state of charge of the battery packs **16***a* and **16***b* is greater than a selected value.

[0087] If the vehicle is started while on-plug, the controller **78** may continue to condition the battery packs **16***a* and **16***b*, to cool the motor circuit thermal load **61** and use of the HVAC system **46** for both heating and cooling the cabin **18** may be carried out.

[0088] When the vehicle is off-plug, battery pack heating may be achieved solely by using the heat in the fluid from the motor circuit (i.e., without the need to activate the battery circuit heater **108**). Thus, while the vehicle is off-plug and on and the battery packs **16***a* and **16***b* require heating, the battery circuit valve **114** may be in the first position so that the battery circuit **60** is not isolated from the motor circuit **56**. Some flow may pass through the third battery circuit conduit **110** for flow balancing purposes, however the refrigerant flow to the chiller **112** is prevented while the battery packs **16***a* and **16***b* require heating. By using low-voltage battery circuit heaters instead of high-voltage heaters for the heaters **108**, a weight-savings is achieved which thereby extends the range of the vehicle.

[0089] When the vehicle is off-plug, battery pack cooling may be achieved by isolating the battery circuit **60** from the motor circuit **56** by moving the battery circuit valve **114** to the second position and by opening the flow of refrigerant to the chiller **112** by moving the flow control valve **140** to its open position, and by running the compressor **30**, as described above in one of the three cooling modes for the battery circuit **60**.

[0090] It will be noted that the battery packs **16***a* and **16***b* may sometimes reach different temperatures during charging or vehicle operation. The controller **78** may at certain times request isolation of the battery circuit **60** from the motor circuit **56** and may operate the battery circuit pump **106** without operating the heater **108** or permitting refrigerant flow to the chiller **112**. This will simply circulate fluid around the battery circuit **60** thereby balancing the temperatures between the battery packs **16***a* and **16***b*.

[0091] Reference is made to FIG. **3**, which shows a graph of battery pack temperature vs. time to highlight several of the rules which the controller **78** (FIG. **2**) follows. In situations where the vehicle is on-plug and the battery packs **16***a* and **16***b* are below a selected minimum charging temperature Tcmin (FIG. **3**), the controller **78** will heat the battery packs **16***a* and **16***b* prior to charging them. Once the battery packs **16***a* and **16***b* reach the minimum Charging temperature Tcmin, some of the power from the electrical source may be used to charge the battery packs **16***a* and **16***b*, and some of the power from the electrical source may continue to be used to heat them. When the battery packs **16***a* and **16***b* reach a minimum charge only temperature Tcomin, the controller **78** may stop using power from the electrical source to heat the battery packs **16***a* and **16***b* and may thus use all the power from the electrical source to charge them. Tcmin may be, for example, about −35 degrees Celsius and Tcomin may be, for example, about −10 degrees Celsius.

[0092] While charging, the controller **78** may precondition the battery packs **16***a* and **16***b* for operation of the vehicle. Thus, the controller **78** may bring the battery packs **16***a* and **16***b* to a desired minimum operating temperature Tomin while on-plug and preferably during charging.

[0093] In situations where the vehicle is on-plug and the battery packs **16***a* and **16***b* are above a selected maximum charging temperature Tcmax, the controller **78** will cool the battery packs **16***a* and **16***b* prior to charging them. Once the battery packs **16***a* and **16***b* come down to the maximum charging temperature Tcmax, power from the electrical source may be used to charge them, while some power may be required to operate the compressor **30** and other components in order to maintain the temperatures of the battery packs **16***a* and **16***b* below the temperature Tcmax. Tcmax may be, for example, about 30 degrees Celsius.

[0094] The battery packs **16***a* and **16***b* may have a maximum operating temperature Tomax that is the same or higher than the maximum charging temperature Tcmax. As such, when the battery packs **16***a* and **16***b* are cooled sufficiently for charging, they are already pre-conditioned for operation. In situations where the maximum operating temperature Tomax is higher than the maximum charging temperature Tcmax, the temperatures of the battery packs **16***a* and **16***b* may be permitted during operation after charging to rise from the temperature Tcmax until they reach the temperature Tomax.

[0095] The maximum and minimum operating temperatures Tomax and Tomin define a preferred operating range for the battery packs **16***a* and **16***b*. In situations where the battery packs **16***a* and **16***b* are below minimum operating temperature or above their maximum operating temperature, the vehicle may still be used to some degree. Within selected first ranges shown at **150** and **152** (based on the nature of the battery packs **16***a* and **16***b*) above and below the preferred operating range the vehicle may still be driven, but the power available will be somewhat limited. Within selected second ranges shown at **154** and **156** above and below the selected first ranges **150** and **152**, the vehicle may still be driven in a limp home mode, but the power available will be more severely limited. Above and below the selected second ranges, the battery packs **16***a* and **16***b* cannot be used. The lower first range **150** may be between about 10 degrees Celsius and about −10 degrees Celsius and the upper first range **152** may be between about 35 degrees Celsius and about 45 degrees Celsius. The lower second range **154** may be between about −10 degrees Celsius and about −35 degrees Celsius. The upper second range may be between about 45 degrees Celsius and about 50 degrees Celsius.

[0096] It will be noted that the pumps **70**, **86** and **106** are variable flow rate pumps. In this way they can be used to adjust the flow rates of the heat exchange fluid through the motor circuit **56**, the cabin heating circuit **58** and the battery circuit **60**. By controlling the flow rate generated by the pumps **70**, **86** and **106**, the amount of energy expended by the thermal management system **10** can be adjusted in relation to the level of criticality of the need to change the temperature in one or more of the thermal loads.

[0097] Additionally, the compressor **30** is also capable of variable speed control so as to meet the variable demands of the HVAC system **46** and the battery circuit **60**.

[0098] Throughout this disclosure, the controller **78** is referred to as turning on devices (for example, the battery circuit heater **108**, the chiller **112**), turning off devices, or moving devices (for example, valve **88**) between a first position and a second position. It will be noted that, in some situations, the device will already be in the position or the state desired by the controller **78**, and so the controller **78** will not have to actually carry out any action on the device. For example, it may occur that the controller **78** determines that the chiller heater **108** needs to be turned on. However, the heater **108** may at that moment already be on based on a prior decision by the controller **78**. In such a scenario, the controller **78** obviously does not actually ‘turn on’ the heater **108**, even though such language is used throughout this disclosure. For the purposes of this disclosure and claims, the concepts of turning on, turning off and moving devices from one position to another are intended to include situations wherein the device is already in the state or position desired and no actual action is carried out by the controller on the device.

[0099] While the above description constitutes a plurality of embodiments of the present invention, it will be appreciated that the present invention is susceptible to further modification and change without departing from the fair meaning of the accompanying claims.

1. A thermal management system for an electric vehicle, the electric vehicle including a traction motor and a passenger cabin, comprising:

a motor circuit for cooling a motor circuit thermal load including the traction motor, wherein the motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet, wherein the motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit;

a cabin heating circuit for heat exchange with a cabin heating circuit thermal load which includes a cabin heater for heating the cabin, the cabin heating circuit thermal load having a cabin heating circuit thermal load inlet and a cabin heating circuit thermal load outlet, a first cabin heating circuit conduit fluidically between the motor circuit and the cabin heating circuit thermal load inlet, a second cabin heating circuit conduit fluidically between the cabin heating circuit thermal load outlet and the motor circuit, a third cabin heating circuit conduit fluidically between the second and first cabin heating circuit conduits, a cabin heating circuit heater positioned to heat fluid in the cabin heating circuit, a cabin heating circuit valve positionable in a first position wherein fluid flow between the motor circuit and the cabin heating circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the cabin heating circuit is permitted, and a cabin heating circuit pump positioned to pump fluid through the cabin heating circuit;

a motor circuit temperature sensor positioned to detect the temperature of fluid in the second motor circuit conduit; and

a controller operatively connected to the cabin heating circuit valve, the cabin heating circuit heater and to the cabin heating circuit pump, wherein the controller is programmed such that when the cabin heating circuit thermal load requires heat and the temperature sensed by the motor circuit temperature sensor is sufficiently high the controller turns off the cabin heating circuit heater and moves the cabin heating circuit valve to the second position, and when the cabin heating circuit thermal load requires heat and the temperature sensed by the motor circuit temperature sensor is sufficiently low the controller turns on the cabin heating circuit heater, operates the cabin heating circuit pump and moves the cabin heating circuit valve to the first position.

2. A thermal management system as claimed in claim **1**, wherein the cabin heating circuit heater is positioned upstream of the cabin heating circuit thermal load inlet.

3. A thermal management system as claimed in claim **2**, further comprising a cabin heating circuit temperature sensor positioned to detect the temperature of fluid downstream from the cabin heating circuit heater and wherein the controller is operatively connected to the cabin heating circuit pump.

4. A thermal management system as claimed in claim **1**, wherein the controller is programmed to activate the cabin heating circuit heater based on the difference between the temperature of fluid from the second motor circuit conduit and a temperature setting from a climate control system in the passenger cabin.

5. A thermal management system as claimed in claim **1**, wherein the motor circuit further includes a radiator bypass valve positioned in the second motor circuit conduit downstream from the cabin heating circuit valve, and a third motor circuit conduit fluidically between the radiator bypass valve and the first motor circuit conduit.

6. A thermal management system as claimed in claim **1**, wherein the motor circuit thermal load includes a transmission control module, and wherein the transmission control module receives electrical current from a high voltage bus and sends a plurality of selected electrical currents to a plurality of destinations.

7. A thermal management system as claimed in claim **6**, wherein the motor circuit thermal load further includes a DC/DC converter, and wherein the DC/DC converter receives electrical current at a first voltage from the transmission control system and outputs an electrical current at a second voltage.

8. A thermal management system as claimed in claim **6**, wherein the cabin heating circuit pump is positioned in the third cabin heating circuit conduit.

9. A thermal management system for an electric vehicle, the electric vehicle including a traction motor and at least one battery pack, the thermal management system comprising;

a motor circuit for cooling a motor circuit thermal load including the traction motor, wherein the motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet, wherein the motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit;

a battery circuit for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack, wherein the battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet, wherein the battery circuit includes a first battery circuit conduit fluidically between the motor circuit and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the motor circuit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a battery circuit heater positioned to heat fluid in the battery circuit, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit;

a motor circuit temperature sensor positioned to detect the temperature of fluid in the second motor circuit conduit; and

a controller operatively connected to the battery circuit valve, the battery circuit heater and to the battery circuit pump, wherein the controller is programmed such that when heating of the battery circuit thermal load is required and the temperature sensed by the motor circuit temperature sensor is sufficiently high the controller turns off the battery circuit heater and moves the battery circuit valve to the second position, and when heating of the battery circuit thermal load is required and the temperature sensed by the motor circuit temperature sensor is sufficiently low the controller turns on the battery circuit heater, operates the battery circuit pump and moves the battery circuit valve to the first position.

10. A thermal management system as claimed in claim **9**, wherein the battery circuit heater is positioned upstream of the battery circuit thermal load inlet.

11. A thermal management system as claimed in claim **9**, wherein the controller is programmed to activate the battery circuit heater based on the difference between the temperature of fluid from the second motor circuit conduit and a target temperature for the battery circuit thermal load.

12. A thermal management system as claimed in claim **9**, further comprising a battery circuit chiller positioned in the battery circuit upstream from the battery circuit thermal load.

13. A thermal management system as claimed in claim **9**, further comprising a battery circuit temperature sensor positioned in the second battery circuit conduit, wherein the controller is programmed to control the operation of the battery circuit heater and the battery circuit valve based in part on the temperature sensed by the battery circuit temperature sensor.

14. A thermal management system as claimed in claim **9**, wherein the battery circuit thermal load includes a battery charge control module, wherein when the vehicle is plugged into an electrical source the battery charge control module receives energy from the electrical source and processes the energy for storage in the battery pack, wherein when the at least one battery pack is below a selected battery pack temperature and the vehicle is plugged into an energy source the controller is programmed to position the battery circuit valve in the second position wherein heat generated in the battery charge control module heats fluid passing through therethrough, wherein the fluid is circulated to the at least one battery pack to heat the at least one battery pack.

15. A thermal management system as claimed in claim **9**, wherein the motor circuit further includes a radiator bypass valve positioned in the second motor circuit conduit, a third motor circuit conduit fluidically between the radiator bypass valve and the first motor circuit conduit.

16. A thermal management system as claimed in claim **9**, wherein the cabin heating circuit pump is positioned in the third cabin heating circuit conduit.

17. A thermal management system for an electric vehicle, the electric vehicle including a traction motor, a passenger cabin and at least one battery pack, the thermal management system comprising:

a motor circuit for cooling a motor circuit thermal load including the traction motor, wherein the motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet, wherein the motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit;

a cabin heating circuit for heat exchange with a cabin heating circuit thermal load which includes a cabin heater for heating the cabin, the cabin heating circuit thermal load having a cabin heating circuit thermal load inlet and a cabin heating circuit thermal load outlet, a first cabin heating circuit conduit fluidically between the motor circuit and the cabin heating circuit thermal load inlet, a second cabin heating circuit conduit fluidically between the cabin heating circuit thermal load outlet and the motor circuit, a third cabin heating circuit conduit fluidically between the second and first cabin heating circuit conduits, a cabin heating circuit heater positioned to heat fluid in the cabin heating circuit, a cabin heating circuit valve positionable in a first position wherein fluid flow between the motor circuit and the cabin heating circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the cabin heating circuit is permitted, and a cabin heating circuit pump positioned to pump fluid through the cabin heating circuit;

a battery circuit for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack, wherein the battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet, wherein the battery circuit includes a first battery circuit conduit fluidically between the second motor circuit conduit upstream from the radiator and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the first motor circuit conduit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a battery circuit heater positioned to heat fluid in the battery circuit, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit;

a motor circuit temperature sensor positioned to detect the temperature of fluid in the second motor circuit conduit; and

a controller operatively connected to the cabin heating circuit valve to control the flow of fluid between the motor circuit and the cabin heating circuit and operatively connected to the battery circuit valve to control the flow of fluid between the motor circuit and the battery circuit, such that heat transferred to fluid in the motor circuit by the motor circuit thermal load is removed from the fluid by at least one of the group selected from the cabin heating circuit thermal load, the battery circuit thermal load and the radiator.

18. A thermal management system for an electric vehicle, the electric vehicle including a traction motor and at least one battery pack, the thermal management system comprising:

a battery circuit for controlling the temperature of a battery circuit thermal load including the at least one the battery pack including a battery circuit thermal load inlet and a battery circuit thermal load outlet, wherein the battery circuit includes a first battery circuit conduit extending to the battery circuit thermal load inlet, a second battery circuit conduit from the battery circuit thermal load outlet, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, and a battery circuit pump in the first battery circuit conduit configured to pump fluid through the battery circuit;

a battery charge control module, wherein when the vehicle is plugged into an electrical source the battery charge control module receives energy from the electrical source and processes the energy for storage in the at least one battery pack, wherein when the at least one battery pack is below a selected battery pack temperature and the vehicle is plugged into an electrical source the controller is programmed to position the battery circuit valve in the second position wherein heat generated in the battery charge control module heats fluid passing through therethrough, wherein the fluid is circulated to the at least one battery pack to heat the at least one battery pack; and

a battery circuit heater positioned to heat fluid in the battery circuit, wherein the battery circuit heater is configured to operate with an inlet voltage of 12VDC.

19. A thermal management system as claimed in claim **18**, further comprising a motor circuit for cooling a motor circuit thermal load including the traction motor, wherein the motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet, wherein the motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit,

wherein the first and second battery circuit conduits connect to the motor circuit; and

wherein the battery circuit includes a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and wherein the battery circuit valve is configurable in a first configuration for sending fluid from the battery pack outlet to the first motor circuit conduit, and is configurable in a second configuration for sending fluid from the battery pack outlet to the third battery circuit conduit.

20. A thermal management system for an electric vehicle, the electric vehicle including a traction motor and at least one battery pack, the thermal management system comprising:

a motor circuit for cooling a motor circuit thermal load including the traction motor, wherein the motor circuit thermal load has a motor circuit thermal load inlet and a motor circuit thermal load outlet, wherein the motor circuit includes a radiator, a first motor circuit conduit fluidically between the radiator and the motor circuit thermal load inlet, a second motor circuit conduit fluidically between the radiator and the motor circuit thermal load outlet, and a motor circuit pump positioned to pump fluid through the motor circuit;

a battery circuit for controlling the temperature of a battery circuit thermal load which includes the at least one battery pack, wherein the battery circuit thermal load has a battery circuit thermal load inlet and a battery circuit thermal load outlet, wherein the battery circuit includes a first battery circuit conduit fluidically between the second motor circuit conduit upstream from the radiator and the battery circuit thermal load inlet, a second battery circuit conduit fluidically between the battery circuit thermal load outlet and the first motor circuit conduit, a third battery circuit conduit fluidically between the second battery circuit conduit and the first battery circuit conduit, a chiller positioned to cool fluid in the battery circuit, the chiller having a refrigerant inlet and a refrigerant outlet, a battery circuit valve positionable in a first position wherein fluid flow between the motor circuit and the battery circuit is substantially prevented and a second position wherein fluid flow between the motor circuit and the battery circuit is permitted, and a battery circuit pump positioned to pump fluid through the battery circuit;

a main cooling circuit including a compressor, a first cooling circuit conduit positioned upstream of the compressor and positioned for receiving refrigerant from the refrigerant outlet of the evaporator and for receiving refrigerant from the refrigerant outlet of the chiller, a condenser positioned downstream from the compressor, a second cooling circuit conduit positioned downstream of the condenser and positioned for delivering refrigerant to the refrigerant inlet of the chiller and to the refrigerant inlet of the evaporator and a chiller refrigerant flow control valve positioned for controlling the flow of refrigerant through the chiller;

a motor circuit temperature sensor positioned to detect the temperature of fluid in the second motor circuit conduit; and

a controller operatively connected to the chiller refrigerant flow control valve, the evaporator refrigerant flow control valve, the battery circuit valve, the battery circuit pump and the compressor, wherein the controller is programmed to open the chiller refrigerant flow control valve based on a comparison of the temperature sensed by the motor circuit temperature sensor and a target temperature for the battery circuit thermal load, and to open the evaporator refrigerant flow control valve based on a temperature setting of a climate control system for the passenger cabin.

21. A thermal management system as claimed in claim **20**, wherein the vehicle includes a passenger cabin and an evaporator for controlling the temperature of the passenger cabin, the evaporator having a refrigerant inlet and a refrigerant outlet, and wherein the thermal management system includes an evaporator refrigerant flow control valve positioned for controlling the flow of refrigerant through the evaporator, wherein the controller is operatively connected to the evaporator refrigerant flow control valve.

22. A thermal management system as claimed in claim **21**, wherein the chiller refrigerant flow control valve and the evaporator refrigerant flow control valve are the same valve.

* * * * *