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(54) **Title:** CONTROL SYSTEM FOR A VEHICLE

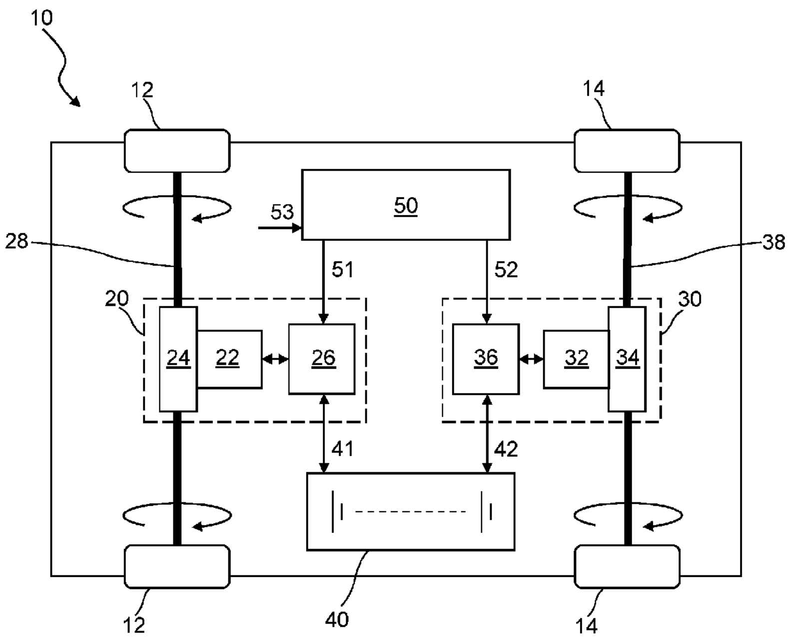

FIG. 2

(57) **Abstract:** A vehicle (100) comprises a first propulsion unit (20) comprising an induction motor (22) having a stator (80) and a rotor (90). A control system (50) for the vehicle is configured to operate the induction motor (22) in a first operating mode and in a second operating mode to achieve a first torque value. In the first operating mode, the induction motor (22) is operated with a first stator current and a first rotor current. In the second operating mode, the induction motor (22) is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, and the second stator current is greater than the first stator current. The control system (50) is configured to operate the induction motor (22) in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor (90).

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CONTROL SYSTEM FOR A VEHICLE

TECHNICAL FIELD

The present disclosure relates to a control system for a vehicle. Aspects of the invention relate to a control system for a vehicle, a propulsion system for a vehicle, a vehicle comprising the control system, a method for controlling a vehicle and a non-transitory computer readable medium.

BACKGROUND

Electric vehicles (EVs) comprise an Electric Drive Unit (EDU) which drives wheels of the vehicle. An EDU may use a permanent magnet (PM) motor or an induction motor (IM). IM-based EDUs have some advantages, but also have some challenges, such as periods of operation with high torque demands.

It is an aim of the present invention to address one or more of the disadvantages associated with the prior art.

SUMMARY OF THE INVENTION

Aspects and embodiments of the invention provide a control system for a vehicle. Aspects of the invention relate to a control system for a vehicle, a propulsion system for a vehicle, a vehicle comprising the control system, a method for controlling a vehicle and a non-transitory computer readable medium as claimed in the appended claims.

According to an aspect of the present invention there is provided a control system for a vehicle, the vehicle comprising a first propulsion unit comprising an induction motor having a stator and a rotor, the control system comprising one or more processors collectively configured to:

operate the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operate the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the control system is configured to operate the induction motor in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor.

An advantage of the control system is that the induction motor can meet a torque demand for a longer period of time without overheating. The second operating mode has lower rotor conduction (I^2R) losses to achieve the same torque value and therefore the induction motor generates less heat in the rotor when it is operated in the second operating mode. The first operating mode is more efficient than the second operating mode. Operating in the first operating mode and in the second operating mode in dependence, at least in part, on a temperature of the rotor has an advantage of conserving battery energy. The control system can operate in the more efficient first operating mode until the temperature of the rotor requires the control system to operate in the less efficient second operating mode.

The temperature of the rotor may be a measured temperature of the rotor, such as a temperature measured by a temperature sensor. Alternatively, the temperature of the rotor may be a predicted temperature of the rotor, such as a predicted temperature calculated by a thermal model of the induction motor. An advantage of predicting the temperature of the induction motor, rather than measuring an actual temperature of the induction motor, is that is possible to obtain a temperature for a part of the induction motor which it is not possible to reliably measure with a temperature sensor.

The control system may operate the induction motor in the first operating mode or in the second operating mode by comparing the temperature of the rotor with a threshold value. Additionally, or alternatively, the control system may operate the induction motor in the first operating mode or in the second operating mode in dependence on an increase or a decrease in temperature over a period of time (i.e. a positive or negative temperature delta).

Optionally, the control system is configured to determine a required torque for the induction motor and to operate the induction motor in the first operating mode or in the second operating mode in dependence on a magnitude of the required torque.

Optionally, the control system is configured to operate the induction motor in the second operating mode when the magnitude of the required torque is above a threshold value of torque.

Optionally, the control system is configured to determine a required torque for the induction motor and to operate the induction motor in the first operating mode or in the second operating mode in dependence on a period of time for which the required torque is continuously needed.

Optionally, the control system is configured to operate the induction motor in the second operating mode when the time for which the required torque is needed is above a threshold value of time.

Optionally, the control system is configured to operate the induction motor in the second operating mode in dependence on one or more of: a type of terrain under, or near to, the vehicle; a type of surface under, or near to, the vehicle; a gradient of surface under, or near to, the vehicle; a location of the vehicle; a speed of the vehicle; a temperature of the induction motor.

Optionally, the control system is configured to operate the induction motor in the second operating mode when the type of terrain under, or near to, the vehicle is one or more of: sand; snow; mud. These types of terrain may require a high torque demand for an extended period of time. Selecting the second operating mode in dependence on detecting these types of terrain has an advantage of pre-emptively reducing heat generated in the rotor, thereby allowing safe operation for an extended period of time.

Optionally, the control system is configured to receive an input selecting a driving mode for the vehicle and to the operate the induction motor in the second operating mode in dependence on the input. For example, the driving mode may be a sand driving mode, a snow driving mode or a mud driving mode. These driving modes may require a high torque demand for an extended period of time. Selecting the second operating mode in dependence on these driving modes has an advantage of pre-emptively reducing heat generated in the rotor, thereby allowing safe operation for an extended period of time.

Optionally, the control system is configured to operate the induction motor exclusively in the first operating mode when regenerating electrical energy.

Optionally, the vehicle comprises a second propulsion unit and the control system is configured to:

determine an amount of required torque from the first propulsion unit and an amount of required torque from the second propulsion unit; and at least one of:

operate the induction motor in the second operating mode when the amount of required torque from the first propulsion unit is above a threshold value of torque;

operate the induction motor in the second operating mode when the amount of required torque from the first propulsion unit is more than a percentage of a total of the amount of required torque from the first propulsion unit and the amount of required torque from the second propulsion unit.

This has an advantage of reducing heat generated in the rotor of the first propulsion unit, thereby allowing safe operation for an extended period of time.

According to another aspect of the invention, there is provided a propulsion system for a vehicle comprising the first propulsion unit and the control system of the previous aspect.

Optionally, the propulsion system comprises a second propulsion unit of a different type to the first propulsion unit, such as a permanent magnet motor.

Optionally, the first propulsion unit is configured to drive a front axle of the vehicle and the second propulsion unit is configured to drive a rear axle of the vehicle.

According to another aspect of the invention, there is provided a vehicle comprising the control system of the previous aspects or the propulsion system of the previous aspect.

According to another aspect of the invention, there is provided a method for controlling a vehicle, the vehicle comprising a first propulsion unit comprising an induction motor having a stator and a rotor, the method comprising:

operating the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operating the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the method operates the induction motor in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor.

An advantage of the method is that the induction motor can meet a torque demand for a longer period of time without overheating. The second operating mode has lower rotor conduction (I^2R) losses and therefore the induction motor generates less heat in the rotor when it is operated in the second operating mode.

The control system comprises one or more controllers collectively comprising at least one electronic processor having an electrical input for receiving an input signal; and at least one memory device electrically coupled to the at least one electronic processor and having instructions stored therein; and wherein the at least one electronic processor is configured to access the at least one memory device and execute the instructions thereon so as to:

operate the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operate the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the control system is configured to operate the induction motor in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor.

According to another aspect of the invention, there is provided a non-transitory computer readable medium comprising computer readable instructions that, when executed by a processor, cause performance of the method.

According to another aspect of the present invention there is provided a control system for a vehicle, the vehicle comprising a first propulsion unit comprising an induction motor having a stator and a rotor, the control system comprising one or more processors collectively configured to:

operate the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operate the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the control system is configured to operate the induction motor in the first operating mode or in the second operating mode.

Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 shows a vehicle in accordance with an embodiment of the invention;

Figure 2 schematically shows functional units and a control system of the vehicle;

Figure 3 shows an example of an induction motor which can be used to drive an axle of the vehicle;

Figure 4 shows the induction motor of Figure 3 and power electronics for the motor;

Figure 5 shows a controller for use in the vehicle of Figure 2;

Figure 6 shows an example set of stored data for use by the control system;

Figure 7 shows another example of stored data for use by the control system;

Figure 8 shows a cooling system for the induction motor;

Figure 9 shows an example of a model to predict temperature of the induction motor;

Figure 10 shows an example time line for controlling operation of the induction motor;

Figure 11 shows a flow diagram of an example of a method of operating an induction motor performed by the control system;

Figure 12 shows a flow diagram of another example of a method of operating an induction motor performed by the control system;

Figure 13 shows an equivalent circuit of an induction motor; and

Figure 14 shows a vector diagram for the circuit of Figure 13.

DETAILED DESCRIPTION

Figures 1 and 2 show an example of an electric vehicle (EV) 10. The electric vehicle 10 comprises a battery or battery pack 40. The battery 40 may be recharged from an external electrical source. The electric vehicle 10 comprises a pair of front wheels 12 and a pair of rear wheels 14. The front wheels 12 are driven by a first electric drive unit (EDU) 20. The first EDU 20 comprises a first motor 22, a front transmission 24 and power electronics 26. The rear wheels 14 are driven by a second electrical drive unit (EDU) 30. The second EDU 30 comprises a second motor 32, a rear transmission 34 and power electronics 36. The first EDU 20 and the second EDU 30 each receive a DC supply from battery 40. The first EDU 20 can be called a first propulsion unit and the second EDU 30 can be called a second propulsion unit.

A controller 50 controls operation of the first EDU 20 and the second EDU 30. In operation, the controller 50 controls the power output of each of the EDUs 20, 30 to supply torque to the wheels 12, 14. Power electronics 26 comprise an inverter which converts the DC supply from battery 40 to an

AC supply to drive the first motor 22. The first motor 22 drives the front transmission 24 which, in turn, drives the front axle 28 to apply torque to the front wheels 12. Power electronics 36 comprise an inverter which converts the DC supply from battery 40 to an AC supply to drive the second motor 32. The second motor 32 drives the rear transmission 34 which, in turn, drives the rear axle 38 to apply torque to the rear wheels 14.

In one example, the first motor 22 is an induction motor (IM) and the second motor 32 is a permanent magnet (PM) synchronous motor. An induction motor can also be called an induction machine, as it is capable of operating as a motor and as a generator.

The induction motor 22 comprises a stator with electrical windings and a rotor with electrical conductors. The induction motor is operated by supplying an AC supply to the stator windings. There is no electrical supply to the rotor. The AC supply to the stator windings generates a rotating magnetic field (a stator field, or stator flux) which induces current flow in the conductors of the rotor. Interaction between the rotating magnetic field and induced current flow in the rotor conductors causes movement of the rotor.

In contrast, a PM motor has a stator with electrical windings and a rotor with permanent magnets and rotor laminations. The PM motor is operated by supplying an AC supply to the stator windings. There is no electrical supply to the rotor. The stator windings provide a rotating magnetic field (a stator field, or stator flux). Interaction between the rotating magnetic field and rotor features (i.e. permanent magnets and laminations) causes movement of the rotor.

An induction motor and a PM motor have different electrical characteristics. Both motors have losses in the stator and in the rotor. The losses mainly fall into two groups: copper losses and iron losses. Copper losses are due to resistive heating effects of current flow through conductors, such as current flow through the stator windings and, in the case of the induction motor, current flow through the electrical conductors of the rotor. Iron losses are due to the effects of magnetic flux pulsation in the stator and rotor, such as hysteresis and eddy currents. In a PM motor a majority of the losses occur in the stator, such as 95% of total losses in the stator. In an induction motor the losses are more evenly distributed between the stator and the rotor, such as 50% of total losses in each of the stator and the rotor. This means that the induction motor will generate more heat in the rotor, particularly at high rotor currents. A cooling system is provided for the induction motor but this has a limited ability to remove heat from the rotor. Therefore, some additional strategy is needed to cope with rotor heating when the induction motor is operated at high levels of rotor current for extended periods.

The controller 50 may operate the vehicle in the following ways:

(i) Rear-wheel drive (RWD). Torque is only supplied to the rear wheels 14 by operating the second motor 32 to drive the rear wheels 14. The front wheels 12 are not driven by the first motor 22;

(ii) All-wheel drive (AWD). Torque is supplied to the rear wheels 14 and to the front wheels 12 by operating the second motor 32 to drive the rear wheels 14 and operating the first motor 22 to drive the front wheels 12;

(iii) Front-wheel drive (FWD). Torque is only supplied to the front wheels 12 by operating the first motor 22 to drive the front wheels 12. The rear wheels 14 are not driven by the second motor 32.

In some vehicles, the controller 50 may only operate according to options (i) and (ii), and may not operate according to option (iii).

For option (ii), the controller 50 can divide a total amount of torque between the rear wheels 14 and the front wheels 12 according to a torque ratio, called a torque split. In most driving conditions, the torque split will deliver a higher portion of the total torque via the rear wheels 14, such as 80:20 (i.e. 80% to the rear wheels, 20% to the front wheels) or 60:40. In some driving conditions, such as driving in terrain such as sand, snow or mud, a more even torque split is desirable. For example, the total torque may be divided 50:50 (i.e. 50% to the rear wheels, 50% to the front wheels), or near to 50:50. Operating the induction motor 22 at high torque levels can generate an undesirable amount of heat in the rotor.

An example induction motor 22 is shown in Figures 3 and 4. Figure 3 shows a cross-section through a 3-phase two pole induction motor 22. The induction motor 22 has a stator 80 and a rotor 90. The rotor 90 is positioned within the stator 80. The rotor 90 and rotor shaft 94 can rotate relative to the stator 80. An air gap 98 separates the stator 80 and the rotor 90. Three sets of phase windings 84 are located in slots 86 of the stator 80.

Each set of phase windings 84 is electrically connected to one of the electrical phases of the AC signal. In this example, the phase windings are labelled A, B, C. A single pair of slots 86 is shown per phase. Each of the phase windings is looped around the stator 80. For example, the phase winding of phase A comprises a continuous electrical path which carries current in a direction perpendicularly into the drawing (conductor A) and in a direction perpendicularly out of the drawing (conductor -A). Figure 3 shows a single pair of slots 86 per phase, but there can be a larger number of slots 86 distributed over an interior perimeter of the stator 80. For example, there may be a first set of slots distributed around a portion of the stator 80 and a second set of slots distributed over another portion of the stator 80 on the opposing side of the stator 80. Figures 3 and 4 show one possible example of an induction motor. The induction motor can have a higher number of poles, such as 4, 6, or 8 poles, or a different number of poles. The induction motor can have a higher number of phases.

The rotor 90 comprises a plurality of electrical conductors 92 which are aligned longitudinally along the length of the rotor, parallel to the rotor shaft 94. The electrical conductors 92 are positioned at, or close to, the outer surface of the rotor 90. The electrical conductors 92 are electrically connected together (not shown) at each longitudinal end of the rotor 90 by a respective end ring. The electrical conductors 92 and end rings together resemble a cage, and may be called a squirrel cage. Other types of rotor are possible.

Figure 4 shows the windings A, B, C supplied by a 3-phase AC electrical signal 27 from power electronics 26. Power electronics 26 converts a DC supply 41 from the battery 40 to a 3-phase AC supply 27. Control signal 51 controls operation of the power electronics 26. For example, control signal 51 can control amplitude and frequency of the AC signal 27. In a known way, the 3-phase AC signal causes a rotating magnetic field around the stator 80. This rotating magnetic field induces current flow in the conductors 92 of the rotor 90. Interaction between the rotating magnetic field of the stator and current flow in the rotor conductors 92 causes a torque which turns the rotor shaft 94. At an operating point of the electrical machine (motor), the speed of the rotating magnetic field of the stator (n_s) and the speed of the rotor (n_r) are different. The ratio of the difference of speeds (n_s – n_r) and the speed of the rotating magnetic field (n_s) is called slip. Slip has a positive value when the induction motor operates as a motor.

The power electronics 26 is configured to generate the AC signal 27 with a frequency and amplitude which cause a stator current I_s to flow in the stator windings, a rotor current I_r to flow in the electrical conductors of the rotor, and generate a torque T. The power electronics 26 can vary one or more of: (i) the frequency of the AC signal 27; and (ii) stator current I_s of the AC signal 27 to vary the operating point of the induction motor 22. The stator frequency relates to rotor frequency at identical rotor speed values. The power electronics 26 is configured to generate an AC signal at a frequency which results in a required rotor frequency at identical rotor speed values.

It has been found that the induction motor can be driven at a plurality of different operating points which achieve the same value of torque T at identical rotor speed values. These different operating points have different efficiencies. The term “efficiency” means the portion of electrical input power which is converted to output (mechanical) power. Stated another way:

$$\text{Efficiency} = P_{out}/P_{in},$$

where: P_out is output power and P_in is input power.

For example, consider two operating points:

- Operating point 1: frequency = F1, I_s = IS1; I_r = IR1; torque = T1; Efficiency = E1;
- Operating point 2: frequency = F2, I_s = IS2; I_r = IR2; torque = T2; Efficiency = E2;

  where: IS2 > IS1; IR2 < IR1; T2 = T1; and E2 < E1.

These two operating points achieve the same value of torque, with T1 = T2. Operating point 2 has a lower rotor current IR2, but requires a higher stator current IS2 and has a lower efficiency E2. Operating Point 2 requires a disproportionately large increase in stator current (compared to the reduction in rotor current), and therefore Operating point 2 requires more electrical power for the same torque, and has a lower efficiency than Operating point 1. The two operating points have different slip values.

For a given value of torque, the total number of possible operating points may be two, or may be a larger number, e.g. three, four, ten, twenty etc.

It is desirable to operate the induction motor with a high efficiency to maximise the range of the vehicle for one charging cycle of the battery. That is, the best use is made of the limited stored electrical energy by converting electrical energy as efficiently as possible into mechanical torque. Under some driving conditions it is desirable to operate the induction motor with a lower rotor current and a lower efficiency to reduce the operating temperature of the rotor. This allows the induction motor to safely generate torque for a longer period of time. During an extended period of driving in sand, snow or mud, a high torque is required for a relatively long period of time. For example, high torque may be required for tens of minutes. Operating the induction motor at operating point 1 (above) during these driving conditions will generate an undesirable amount of heat. However, operating the induction motor at operating point 2 during these driving conditions generates a reduced amount of heat in the rotor, allowing safe operation over a longer period of time.

A detailed mathematical explanation of using a lower rotor current is provided at the end of the description. Considering a set of operating points for the induction motor which generate the same torque, the operating points with a lower rotor current have reduced rotor current losses due to the reduced rotor current. These operating points have increased losses in the stator. There are increased copper losses due to the higher stator current flowing in the windings, and higher iron losses due to the higher amount of magnetic flux (higher flux density) in the stator. These operating points with reduced rotor current can be viewed as moving a portion of the total losses from the rotor side of the induction motor to the stator side of the induction motor. Operating points with a lower rotor current have a higher portion of losses in the stator, and higher overall losses. However, this can be tolerated because it is easier to cool the stator and therefore the induction motor can be operated for longer.

It has been found that there is a non-linear relationship between the reduction in rotor current and the corresponding increase in stator current. For example, a 50% reduction in rotor current (e.g. a decrease from 60 A to 30 A) may require a much larger increase in stator current (e.g. an increase from 100 A to 350 A).

Figure 5 schematically shows the control system. The control system comprises one controller 50, although it will be appreciated that this is merely illustrative. The controller 50 comprises at least one processor 56 which may be any type of processor for executing instructions to control the operation of the system. The processor 56 is electrically connected to other components of the controller via one or more buses 57. Processor-executable instructions 48 may be provided using any data storage device or computer-readable media, such as memory 58. The processor-executable instructions 48 comprise instructions for implementing the functionality of the described methods. The storage/memory 58 is of any suitable type such as non-volatile memory, a magnetic or optical storage device. The processor 56 is configured to access the memory 58 and execute the stored instructions 48. Memory 58, or a separate memory/storage stores data 60 used by the processor 56. Data 60 may comprise data which defines a plurality of operating points of the induction motor 22. Instructions 48 may comprise rules for selecting between plurality of operating points of the induction motor 22. The controller 50 comprises an input interface 54. The input interface 54 is configured to receive one or more input signals 53. The controller 50 comprises an output interface 55. The output interface 55 is configured to output outputs, such as the control signal 51 to control the first motor 22 and the control signal 52 to control the second motor 32. Memory 58 stores instructions 49 which implement a mathematical, or algorithmic, thermal model of the induction motor to predict temperature of the induction motor 22.

The controller 50 receives various input signals 53. The input signals 53 may comprise one or more of:

an input selecting a driving mode (e.g. sand driving mode, snow driving mode, mud driving mode.) The input may be received from a user interface of the vehicle. The input represents a manual selection of a driving mode by a user.

a demand for acceleration or a demand for speed (e.g. from an accelerator pedal or from an automated control system of the vehicle);

a speed of the vehicle (e.g. from a rotation sensor associated with one of the wheels, or from a rotation sensor associated with one of the motors 22, 32);

an indication of a type of terrain under, or near to, the vehicle;

an indication of a type of surface under, or near to, the vehicle;

a gradient of surface under, or near to, the vehicle;

a location of the vehicle (which may be used to determine terrain, e.g. desert);

a temperature of the induction motor (e.g. of the rotor, or the rotor and stator).

The controller 50 outputs a control signal 51 to control operation of the power electronics 26 which drive the first motor 22. The controller 50 outputs a control signal 52 to control operation of the power electronics 36 which drive the second motor 32. The controller 50 is configured to use one or more of the input signals 53 and stored data, to generate output signals 51, 52.

Figure 6 shows an example of the stored data 60. The stored data comprises data which defines possible (candidate) operating points for the induction motor 22. Each operating point is defined by a set of data values comprising: a stator current (I_s) and a rotor current (I_r). The set may comprise a stator frequency f and/or a rotor frequency. The candidate operating points defined in this table all deliver the same torque T but have different efficiencies. A similar set of candidate operating points is provided for other values of torque. The stored data 60 is a look up table.

The controller 50 is configured to selectively operate the induction motor 22 in a first operating mode and in a second operating mode. In the first operating mode, the induction motor 22 is operated at an operating point (selected from the set of candidate operating points) which has a good, or high, efficiency. This may require a large rotor current. In the second operating mode, the induction motor 22 is operated at an operating point (selected from the set of candidate operating points) which has a lower efficiency. This requires a lower rotor current, and therefore allows the induction motor 22 to operate for a longer period of time without overheating.

Figure 6 shows a table of stator current (I_s), rotor current (I_r) and frequency (f) values for one value of torque T1. In this table, the stator current (I_s) values are arranged in numerical order. The direction of the arow indicates the direction towards the highest numerical value. Stator current increases in value towards the top of the table. The corresponding rotor current (I_r) values generally decrease in value towards the top of the table.

Dashed boxes 61, 62 indicate two different operating points of the induction motor. Operating point 61 is selected for a first operating mode of the motor for normal driving. Operating point 62 is selected for a second (reduced rotor current) operating mode of the motor.

Current flow in the stator windings and the rotor conductors of the induction motor 22 generates heat. The induction motor can be cooled by a cooling system, such as by passing a coolant fluid through the induction motor. However, there is a practical limit on the rotor current and on the stator current for safe operation. For example, the induction motor may have limits (in the second, reduced rotor current, operating mode) of: stator current limit = 200 A, rotor current limit = 40 A. The controller 50 may be configured to select one of the possible operating points based on the current limits. For example, if the controller 50 determines that the induction motor should operate in the second, reduced rotor current, operating mode it determines if any of the possible sets of (I_s, I_r) values 60 are suitable. Using the current limits above (I_s = 200 A, I_r = 40 A) the controller determines if any of the possible sets of (I_s, I_r) values in the stored data 60 have I_S < 200 A and I_r < 40 A.

When operating with reduced rotor current, there is a maximum rotor current (I_r) value for safe operation of the induction motor. Similarly, there is a maximum stator current (I_s) value for safe operation of the induction motor. These values can be obtained in advance from actual test analysis, or from a thermal model of the motor. The controller 50 may be configured to select an operating point for the induction motor based on one or more of the maximum current values.

The controller 50 is configured to select an operating mode for the induction motor 22, and therefore an operating point for the induction motor 22, based on the inputs 53.

There are various ways of storing the data used by the controller 50. For example, the table 60 shown in Figure 6 stores data for a plurality of different operating points which provide the same torque T1. This table may comprise data for a plurality of operating points for other torque values T2, T3 etc.

Figure 7 shows another way of storing data used by the controller 50. There is a first data table 71 and a second data table 72. Each of these data tables 71, 72 may be called a map, as it maps values of torque (T1, T2, T3,...) to values of operating parameters (I_s, I_r, f) to achieve the torque values. When the controller 50 operates in the first operating mode, it uses the first data table 71 to map a required torque value to values of operating parameters. When the controller 50 operates in the second (reduced rotor current) operating mode, it uses the second data table 72 to map a required torque value to values of operating parameters. A value of torque T3 corresponds to an operating point 73 in data map 71 and to an operating point 74 in data map 72. The operating point 73 in data map 71 has different values for the operating parameters (I_s, I_r, f) compared to operating point 74 in data map 72.

Figure 8 schematically shows an example of a cooling system 140 for the induction motor 22. The cooling system 140 is configured to circulate coolant (e.g. oil) around the motor 22 to remove excess heat from the induction motor 22. The cooling system 140 comprises a sump 141 for storing a quantity of coolant, a pump 142 for circulating coolant around the cooling system, and a heat exchanger 144. The heat exchanger 144 is configured to remove heat from the coolant. Coolant is passed through a housing 148 which surrounds the induction motor 22. Coolant may pass through at least part of an interior of the induction motor 22, such as through the stator of the induction motor 22. Coolant may be sprayed onto ends of the rotor of the induction motor. Information is obtained from the cooling system. Pump speed 143 is output from a sensor at the pump 142. Sensors 145 in the flow path output: coolant temperature 146; coolant pressure and/or flow rate 147. A temperature sensor 149 in the inductor motor 22 measures a temperature of a part of the induction motor 22 and outputs a motor temperature 150. The temperature sensor 149 may measure stator winding temperature, or a temperature of another part of the induction motor.

Figure 9 schematically shows a module 160 which predicts current temperature of the induction motor 22. The module 160 is configured to calculate a predicted current temperature of the induction motor 22. The module 160 may predict a temperature of one or more of: the rotor of the induction motor 22; the stator of the induction motor 22. The module 160 may predict a temperature of a part of the induction motor 22 which is not measured by the temperature sensor 149. For example, the module 160 may predict a temperature of the rotor of the induction motor.

The module 160 implements a thermal model of the motor 22. This can be a mathematical or algorithmic model in the form of an equation, or a set of equations, which calculate temperature of the motor as a function of input parameters. The module 160 receives one or more inputs 161. The module 160 outputs a predicted temperature 162. Examples of inputs include one or more of: oil temperature (of cooling oil for the IM) 146; oil flow rate (of cooling oil for the IM) 147; oil pressure (of cooling oil for the IM) 147; oil pump speed 143; initialised stator temperature 150; EM torque requested; DC voltage; EM speed measured; IM operating mode.

The thermal model may be a calibrated model which is based on actual test data. The thermal model outputs a predicted value of the current IM temperature.

An advantage of predicting the temperature of the motor, rather than measuring an actual temperature of the motor, is that is possible to obtain a temperature for a part of the induction motor which it is not possible to reliably measure with a temperature sensor. For example, the flow of coolant through the motor can make it difficult to measure temperature of the motor, rather than the coolant which is flowing past the temperature sensor. The motor may have localised hot spots at positions away from a position of a temperature sensor 149. Accordingly, a temperature sensor may not take into account the highest temperature regions of the motor. For example, the rotor of the induction motor can have a temperature which is much higher than a winding temperature of the stator, as measured by the temperature sensor 149. The hot spots can be predicted by the thermal model, and can be taken into account when deciding on a suitable operating mode for the motor.

Figure 10 shows an example time line for operating the induction motor 22. Initially, at T0, the controller 50 operates the induction motor in the first operating mode #1. At time T1 the controller makes a change and begins to operate the induction motor in the second (reduced rotor current) operating mode #2. Later, at time T2, the controller makes a further change and returns to operating the induction motor in the first operating mode #1. It will be appreciated that the precise time at which a transition is made between operating modes #1 and #2 can be different from the example shown in Figure 10. For example, the transition #1 -> #2 can occur earlier, or later, than shown. Similarly, the transition #2 -> #1 can occur earlier, or later, than shown. The controller 50 uses control logic to determine when to begin operating in the second (reduced rotor current) operating mode #2, and when to return to operating in the first operating mode #1.

Figure 10 also shows an example time line of rotor temperature. The controller 50 may be configured to begin operating the induction motor in the second (reduced rotor current) operating mode #2 based, at least in part, on the rotor temperature. For example, the rotor temperature may exceed a rotor temperature threshold value. At time T1 the rate of increase of the rotor temperature is reduced due to operating the induction motor in the second (reduced rotor current) operating mode #2. The temperature may level out or decrease after time T1, depending on the torque demand made after time T1.

Figure 11 shows an example of a method 100 of operating the controller for use in vehicle 10 shown in Figure 1. The method 100 may be performed by the controller 50. In particular, the memory 58 may comprise computer-readable instructions 48 which, when executed by the processor 56, perform the method 100.

In block 102, the method determines an operating mode for the induction motor 22. The method selects between the first operating mode and the second operating mode.

When block 102 determines that the induction motor should be operated in the first operating mode, the method proceeds to block 104. The method selects one of the candidate sets of operating point data (e.g. set 61 in the table of Figure 6, or an entry in table 71) which define a suitable operating point. The induction motor is operated in the first operating mode using the set of data values. Block 102 may select from a plurality of possible operating points, wherein each of the operating points comprise a value for the second stator current and a value for the second rotor current to achieve a particular torque value.

When block 102 determines that the induction motor should be operated in the second operating mode, the method proceeds to block 106. The method selects one of the candidate sets of operating point data (e.g. set 62 in the table of Figure 6, or an entry in table 72) which define a suitable reduced rotor current operating point. The induction motor is operated in the second operating mode using the set of data values.

Later, the method returns to block 102 and again determines an operating mode for the induction motor 22. When block 102 determines that the induction motor should continue to operate in the same operating mode, the controller may continue to use the same operating point data values. Alternatively, when block 102 determines that the induction motor should continue to operate in the same operating mode, the controller may select a different operating point (e.g. a different set 61 in the table of Figure 6). For example, a long period of torque demand may increase the rotor temperature and require a lower rotor current. In another example, a decrease in the rotor temperature may allow a higher rotor current and improved efficiency.

The method may return to block 102 in response to one or more inputs. For example, if a user manually de-selects “sand mode”, or if the controller automatically detects that the vehicle is no longer on sandy terrain, the method may return to block 102 and re-evaluate the operating mode for the induction motor.

Some examples of how the controller 50 may select an operating mode in block 102 are now described. In some examples, the controller 50 is configured to select the second operating mode based on a user input. The vehicle may have a user interface which allows a driver to manually select different driving modes. Possible driving modes include “sand driving mode” or “4x4 mode”. If the controller determines that the user has selected the “sand driving mode” or “4x4 mode”, this indicates a high torque is required for an extended period of time. Therefore, the controller 50 selects the second operating mode, and selects an operating point for the induction motor 22 which has a lower rotor current.

In another example, the controller 50 is configured to automatically select the second operating mode based on at least one input which is indicative of surface or terrain. For example, the controller 50 may receive an input indicating that the vehicle is positioned on sandy terrain, or may include logic to determine that the vehicle is positioned on sandy terrain. Some examples of determining surface type or terrain are: by analysing a video input from a camera; by comparing a location of the vehicle with map data which indicates surface/terrain type. Other ways of determining surface/terrain are possible. The controller 50 is configured to automatically select a “Sand driving” driving mode. This indicates a high torque is required for an extended period of time. Therefore, the controller selects the second operating mode, and selects an operating point for the induction motor 22 which has a lower rotor current.

The controller 50 may be configured to select the second operating mode based, at least in part, on a torque split. For example, the controller 50 may be configured to select the second operating mode when the amount of required torque from the induction motor 22 is more than 45% (or some other threshold value) of the total required torque.

The controller 50 may be configured to select the second operating mode based, at least in part, on an amount of required torque from the induction motor.

The controller 50 may be configured to select the second operating mode based, at least in part, on an amount of torque demanded from the induction motor over a preceding period of time. For example, the controller 50 may be configured to select the second operating mode when the magnitude of the required torque has been above a threshold value of torque for a predetermined period of time.

The controller 50 may be configured to select a different operating point (I_s, I_r) for the induction motor after a period of supplying a high level of torque to the front wheels. The controller 50 may be configured to use a thermal model of the induction motor, or a measured temperature associated with the induction motor, to determine when to select a different operating point (I_s, I_r) for the induction motor. The controller 50 may be configured to dynamically select a different operating point (I_s, I_r) for the induction motor while the vehicle is in motion.

It is desirable that the induction motor operates in the most efficient first operating mode when conditions allow. The controller 50 may be configured to change between the second (reduced rotor current) operating mode and the first operating mode when the rotor temperature cools to an acceptable temperature. For example, the controller 50 may determine if the temperature of the rotor is below a rotor temperature threshold value. This may be a predicted temperature of the rotor calculated by the module 160. The rotor temperature threshold value may be a different threshold value compared to the one used to begin operating in the second (reduced rotor current) operating mode. This provides some hysteresis in the control system, and can prevent repeated changes between operating modes. The controller 50 may be configured to determine if the stator temperature is less than a stator temperature threshold value.

Figure 12 shows an example of block 102 of the method 100 of operating the controller, showing some of the logic to select between operating modes for the induction motor. In block 122 a driving mode requiring a prolonged period of torque demand (e.g. “sand mode”) is manually selected by a user. In block 124 the method automatically determines that a prolonged period of torque demand is required, such as by a terrain detection function. Each of these actions (122, 124) cause the method to proceed to block 126.

In block 126 the method determines a required torque based on the selected driving mode or detected terrain. Block 126 may determine a torque split between the front axle and the rear axle. Block 126 may be implemented by a vehicle supervisory controller (VSC).

Blocks 128 and 130 are two decision blocks which determine whether block 102 selects the first operating mode (block 104) or the second operating mode (block 106). Block 128 determines if the temperature of the rotor is above a rotor temperature threshold value. This may be a predicted temperature of the rotor calculated by the module 160 which predicts temperature of the motor, or a measured temperature. For example, a rotor temperature threshold value may be 100 °C, or a different threshold value.

Block 130 determines if the temperature of the stator is below a stator temperature threshold value. This may be a predicted temperature of the stator calculated by the module 160 which predicts temperature of the motor, or a measured temperature.

When the temperature of the rotor is below the rotor temperature threshold value (block 128, N) the method proceeds to block 104 and operates in the first operating mode. This is because the rotor is operating within an acceptable range of temperatures.

When the temperature of the rotor is above the rotor temperature threshold value (block 128, Y) and the temperature of the stator is below the stator temperature threshold value (block 130, Y) the method proceeds to block 106 and operates in the second operating mode. The rotor is running hot, but the stator is cool enough to allow an increased stator current.

When the temperature of the rotor is above the rotor temperature threshold value (block 128, Y) and the temperature of the stator is above the stator temperature threshold value (block 130, N) the method may proceed to block 104. Operating in the second operating mode will increase stator temperature due to the increased stator current. Therefore, if the stator is already too hot, the method does not select the second operating mode as this would further increase the stator temperature. The method may take a different action under these conditions.

Additional, or alternative, decision blocks may be provided in the method. For example, block 102 may proceed to block 106 and operate in the second operating mode if the torque demand has been above a threshold torque value for a predetermined period of time, irrespective of driving mode (block 122) or future torque demand (block 124).

In the example method shown in Figure 12, the decision to operate in the second (reduced rotor current) operating mode is based on a combination of: (i) a driving mode (block 122) or terrain detection (block 124) and (ii) temperature (blocks 128, 130). In another example method, the decision to operate in the second (reduced rotor current) operating mode is based on temperature (alone). This has an advantage that the induction motor can operate in the second (reduced rotor current) operating mode whenever the rotor temperature is high. It also has the advantage that the induction motor can continue to operate in the more efficient first operating mode until there is a need to operate in the less efficient second (reduced rotor current) operating mode. In another example method, the decision to operate in the second (reduced rotor current) operating mode is based on a driving mode (block 122) or terrain detection (block 124), and is independent of temperature. For example, high torque demands of sand driving may lead to increased rotor temperature, so the method pre-emptively selects the second (reduced rotor current) operating mode. In another example method, the decision to operate in the second (reduced rotor current) operating mode is based on a magnitude of required torque required at block 126.

In any of the examples, the decision to operate in the second (reduced rotor current) operating mode may be based on a positive or negative temperature delta. For example, the method may operate in the second (reduced rotor current) operating mode based on an increase in measured or predicted rotor temperature over a period of time. Similarly, the method may operate in the first operating mode based on a decrease in measured or predicted rotor temperature over a period of time.

MATHEMATICAL EXPLANATION

Figure 13 shows an equivalent circuit of an induction machine (IM). The induction machine transforms electrical power into mechanical power (motor regime) and from mechanical power into electrical power (generator regime).

Mechanical power P_m of the induction machine is the product of rotor angular speed and shaft torque:

$$P_m = \omega_{rotor} \cdot T_{shaft} \qquad (1)$$

The shaft torque T_shaft can be calculated as the vectorial product of the space vectors of the base harmonics of currents and flux linkages:

$$T_{shaft} = k \cdot I_s \cdot \psi_s \cdot \sin(\varphi_s) = k \cdot I_r \cdot \psi_r \cdot sin(\varphi_r) = k \cdot I_r \cdot \psi_r \qquad (2)$$

The φ_s angle between the stator current and flux linkages changes by the operation point of the machine. The angle φ_r between the rotor current and flux linkage is constant, and its value is 90°. The quantity k is a constant for a machine.

The relationship between the rotor current and flux linkage is expressed by:

$$\overrightarrow{I_r} \cdot \frac{R_r}{s} = -j \cdot \omega_1 \cdot \overrightarrow{\psi\_r} \qquad (3)$$

Equation (3) is based on the reference directions in the equivalent circuit of the IM.

Figure 14 shows a vector diagram for the equivalent circuit of Figure 13. The vector diagram shows the space vectors of voltages, currents and flux linkages. The vectors are determined in a complex coordinate system, where each vector is expressed with a complex number. The Real axis is called d-axis, and aligned with the rotor flux linkage ψ_r. The I_r rotor current is perpendicular to the ψ_r rotor flux linkage. This means that the reactive power, which creates the ψ_r rotor flux linkage in the rotor, is provided by stator current, because the parallel component of the rotor current with the rotor flux linkage has zero value. In other words, only the I_s current has d-component, which develops the ψ_r rotor flux linkage.

The losses in the IM machines can be divided into two groups: iron losses and copper losses. Iron losses change with the saturation of the magnetic circuit, and with the machine speed. At speed values lower than 30-40% of the peak speed, the iron losses are significantly lower than the copper losses. This ratio of losses determines an efficient direction of reduction of losses in the rotor, which can be achieved by the reduction of the rotor current.

The expression of the conduction losses in the rotor at the three phase induction motors can be calculated on the base of the following expression:

$$P_{conducting-loss-rot} = \frac{3}{2} I_r^2 \cdot R_r \qquad (4)$$

The magnetic circuit of the induction motors is usually non-linear, which means it saturates. For example, an increase of the ψ_r rotor flux linkage by few percent (for example 5% increase) could result in a significantly higher increase of the magnetising component of stator current (for example, 40-50% increase).

In addition to the magnetising component, an excitation component can be distinguished at the stator. This current component of the stator is parallel with the rotor current, with the same magnitude as the rotor current, but with opposite orientation. It provides an excitation which maintains the balance of Magneto Motive Force (MMF) in the IM.

In summary, the magnetising component of the I_s stator current develops the ψ_r rotor flux linkage, until the component of the stator current parallel with the rotor current maintains the balance in the MMF forces of rotor and stator. From equation (4), it can be seen that the conductive losses in the rotor are proportional with the square of the I_r rotor current. This means that the reduction of I_r rotor current significantly reduces the losses in the rotor. This can allow continuous operation of the machine without overheating.

From equation (2), at constant torque the reduction of I_r current results in higher ψ_r rotor flux linkage, which leads to significantly higher magnetising component of stator current. This means the constant torque can be achieved with the constant value of the product of rotor current and flux linkage.

In case when the torque has to be maintained at lower rotor current, then the component of stator current, which maintain the MMF balance will change proportionally with the rotor current. The necessary higher ψ_r rotor flux linkage requires significantly higher magnetising component of the I_s stator current, because the magnetic circuit operates at the higher saturation level. The reduction of I_s stator current component parallel with rotor current will not compensate the rise of the demand of magnetising current component of I_s stator current. This higher I_s current results in higher losses in the stator, and the motor overall losses will also be higher.

<u>Used symbols</u>

P_m	mechanical power on the rotor shaft;
ω_{rotor}	angular speed of the rotor shaft;
T_{shaft}	torque on the rotor shaft;
I_s	the length of space vector of the base harmonic of stator current;
ψ_s	the length of space vector of the base harmonic of stator flux linkage;
φ_s	shift angle between the stator flux linkage and stator current vectors;

I_r	the length of space vector of the base harmonic of rotor current;
ψ_r	the length of space vector of the base harmonic of rotor flux linkage;
φ_r	shift angle between the rotor flux linkage and rotor current vectors;
s	slip $((\omega_1 - \omega_{rotor} \cdot p)/\omega_1)$, where p is the number of pole pairs;
ω_1	the electrical angular speed of the stator current phasor;
j	is the Imaginary operator, it rotates the vectors by 90° in the complex coordinate system;
V_m-machine	voltage space vector(machine phase voltage);
R_s	stator resistance;
R_r	rotor resistance;
L_sσ	leakage inductance of the stator;
L_rσ	leakage inductance of the rotor;
L_m	main field inductance;
I_m	magnetising current (or the current of main field inductance);
E	back emf in the machine, practically it is the voltage on the main field inductance;
ψ_m	the length of space vector of the base harmonic of main field flux linkage;
$\psi_{s\sigma}$	the length of space vector of the base harmonic of stator leakage flux linkage;
$\psi_{r\sigma}$	the length of space vector of the base harmonic of rotor leakage flux linkage;
X_sσ = ω_1·L_ sσ	leakage impedance of the stator;
X_rσ = ω_1·L_ rσ	leakage impedance of the rotor.

While the above description relates to a road vehicle, it will be understood that the invention may be applied to another type of vehicle, such as a rail vehicle with one or more induction motors providing traction, or to induction motors used in other applications.

Some alternatives will now be described.

The induction motor 22 can also be used as a generator. Referring again to Figure 2, rotation of the front wheels 12 and front axle 28 drives the transmission 24 and the rotor shaft of the induction motor 22. The stator windings of the induction motor 22 generate an output AC signal. The output AC signal is converted to DC by power electronics 26 and output to the battery 40.

In the vehicle 10 shown in Figure 2, the first motor 22 motor 22 and the second motor 32 may both be induction motors. The controller may be configured to control the motors 22, 32 to:

(i) operate one of the motors 22, 32 in the first operating mode while the second of the motors 22, 32 is operated in the second (reduced rotor current) operating mode;

(ii) operate both of the motors 22, 32 in the first operating mode;

(iii) operate both of the motors 22, 32 in the second (reduced rotor current) operating mode.

The controller may use the same criterion, or criteria, to select the second (reduced rotor current) operating mode for the motors 22, 32. Alternatively, the controller may use different criterion, or criteria, to select the second (reduced rotor current) operating mode for the motors 22, 32.

Aspects and embodiments of the invention may be further understood with reference to the following non-limiting numbered clauses:

1. An induction motor control system (50) for a vehicle (100) comprising an induction motor (22), the induction motor (22) comprising a stator (80) and a rotor (90), the induction motor control system (50) comprising one or more processors collectively configured to:

operate the induction motor (22) in a first operating mode in which, to achieve a first torque value, the induction motor (22) is operated with a first stator current and a first rotor current and has a first efficiency; and

operate the induction motor (22) in a second operating mode in which, to achieve the first torque value, the induction motor (22) is operated with a second stator current and a second rotor current and has a second efficiency, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current, and the second efficiency is lower than the first efficiency.

2. The induction motor control system of clause 1 configured to select an operating point for the second operating mode from a plurality of possible operating points, wherein each of the possible operating points comprise a value for the second stator current and a value for the second rotor current to achieve the first torque value.

3. The induction motor control system of clause 2 configured to select an operating point for the second operating mode based at least in part on a temperature of the rotor (90).

4. The induction motor control system of clause 3 wherein the rotor temperature is a measured temperature of the rotor (90) or a predicted temperature of the rotor (90).

5. The induction motor control system of any one of clauses 2 to 4 wherein there is a maximum stator current associated with the induction motor (22) and the control system (50) is configured to select an operating point for the second operating mode having a value for the second stator current which is less than the maximum stator current.

6. The induction motor control system of any one of clauses 2 to 5 wherein there is a maximum rotor current associated with the induction motor (22) and the control system (50) is configured to select an operating point for the second operating mode having a value for the second rotor current which is less than the maximum rotor current.

7. The induction motor control system of any one of the preceding clauses configured to operate the induction motor (22) in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor (90).

8. The induction motor control system of clause 7 wherein the rotor temperature is a measured temperature of the rotor (90) or a predicted temperature of the rotor (90).

9. The induction motor control system of any one of the preceding clauses configured to determine a required torque for the induction motor (22) and to operate the induction motor (22) in the first operating mode or in the second operating mode in dependence on a magnitude of the required torque.

10. The induction motor control system of any one of the preceding clauses configured to operate the induction motor in the second operating mode when the magnitude of the required torque is above a threshold value of torque.

11. The induction motor control system of any one of the preceding clauses configured to operate the induction motor in the second operating mode when the magnitude of the required torque has been above a threshold value of torque for a predetermined period of time.

12. A propulsion system for a vehicle comprising an induction motor (22) and the induction motor control system (50) of any one of the preceding clauses.

13. A vehicle comprising the induction motor control system (50) of any one of clauses 1 to 11 or the propulsion system of clause 12.

14. A method for controlling an induction motor for a vehicle, the induction motor comprising a stator and a rotor, the method comprising:

operating the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current and has a first efficiency; and

operating the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current and has a second electrical, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current, and the second efficiency is lower than the first efficiency.

15. Computer readable instructions which, when executed by a computer, are arranged to perform the method according to clause 14.

It will be appreciated that various changes and modifications can be made to the present invention without departing from the scope of the present application.

CLAIMS

1. A control system for a vehicle, the vehicle comprising a first propulsion unit comprising an induction motor having a stator and a rotor, the control system comprising one or more processors collectively configured to:

operate the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operate the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the control system is configured to operate the induction motor in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor.

2. The control system of claim 1 wherein the temperature of the rotor is a measured temperature of the rotor or a predicted temperature of the rotor.

3. The control system of claim 1 or 2 configured to determine a required torque for the induction motor and to operate the induction motor in the first operating mode or in the second operating mode in dependence on a magnitude of the required torque.

4. The control system of claim 3 configured to operate the induction motor in the second operating mode when the magnitude of the required torque is above a threshold value of torque.

5. The control system of any one of the preceding claims configured to determine a required torque for the induction motor and to operate the induction motor in the first operating mode or in the second operating mode in dependence on a period of time for which the required torque is continuously needed.

6. The control system of claim 5 configured to operate the induction motor in the second operating mode when the time for which the required torque is needed is above a threshold value of time.

7. The control system of any one of the preceding claims configured to operate the induction motor in the second operating mode in dependence on one or more of:

a type of terrain under, or near to, the vehicle;

a type of surface under, or near to, the vehicle;

a gradient of surface under, or near to, the vehicle;

a location of the vehicle;

a speed of the vehicle.

8. The control system of claim 7 configured to operate the induction motor in the second operating mode when the type of terrain under, or near to, the vehicle is one or more of: sand; snow; mud.

9. The control system of any one of the preceding claims configured to receive an input selecting a driving mode for the vehicle and to the operate the induction motor in the second operating mode in dependence on the input.

10. The control system of any one of the preceding claims configured to operate the induction motor exclusively in the first operating mode when regenerating electrical energy.

11. The control system of any one of the preceding claims, wherein the vehicle comprises a second propulsion unit and the control system is configured to:

determine an amount of required torque from the first propulsion unit and an amount of required torque from the second propulsion unit; and at least one of:

operate the induction motor in the second operating mode when the amount of required torque from the first propulsion unit is above a threshold value of torque;

operate the induction motor in the second operating mode when the amount of required torque from the first propulsion unit is more than a percentage of a total of the amount of required torque from the first propulsion unit and the amount of required torque from the second propulsion unit.

12. A propulsion system for a vehicle comprising the first propulsion unit and the control system of any one of the preceding claims.

13. A vehicle comprising the control system of any one of claims 1 to 11 or the propulsion system of claim 12.

14. A method for controlling a vehicle, the vehicle comprising a first propulsion unit comprising an induction motor having a stator and a rotor, the method comprising:

operating the induction motor in a first operating mode in which, to achieve a first torque value, the induction motor is operated with a first stator current and a first rotor current; and

operating the induction motor in a second operating mode in which, to achieve the first torque value, the induction motor is operated with a second stator current and a second rotor current, wherein the second rotor current is less than the first rotor current, the second stator current is greater than the first stator current,

wherein the method operates the induction motor in the first operating mode or in the second operating mode in dependence at least in part on a temperature of the rotor.

15. Computer readable instructions which, when executed by a computer, are arranged to perform the method according to claim 14.

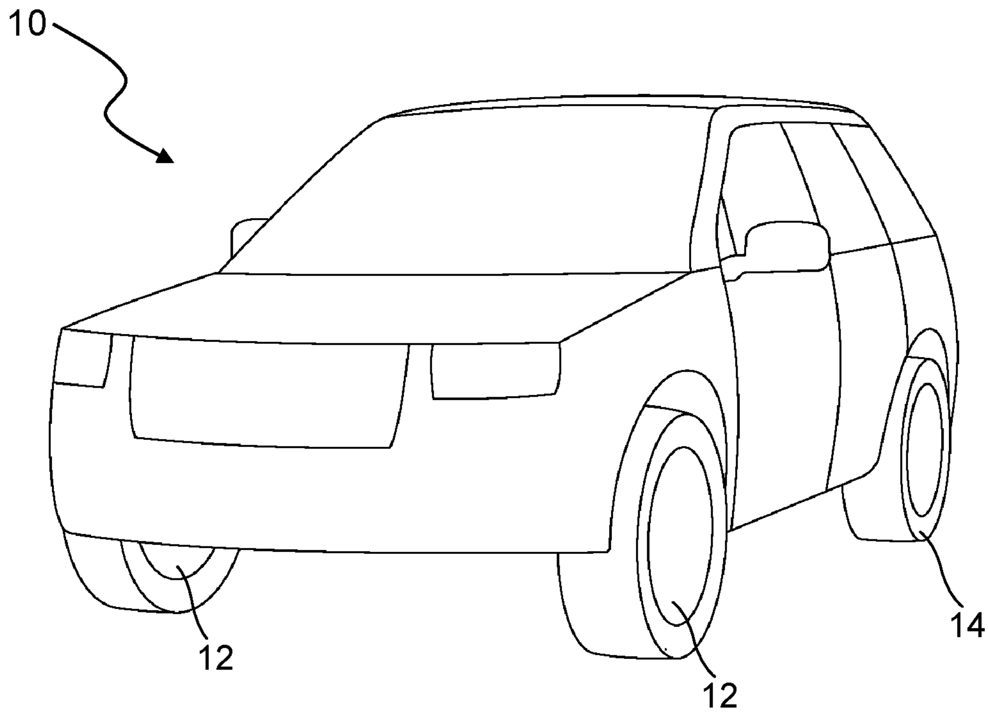
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FIG. 1

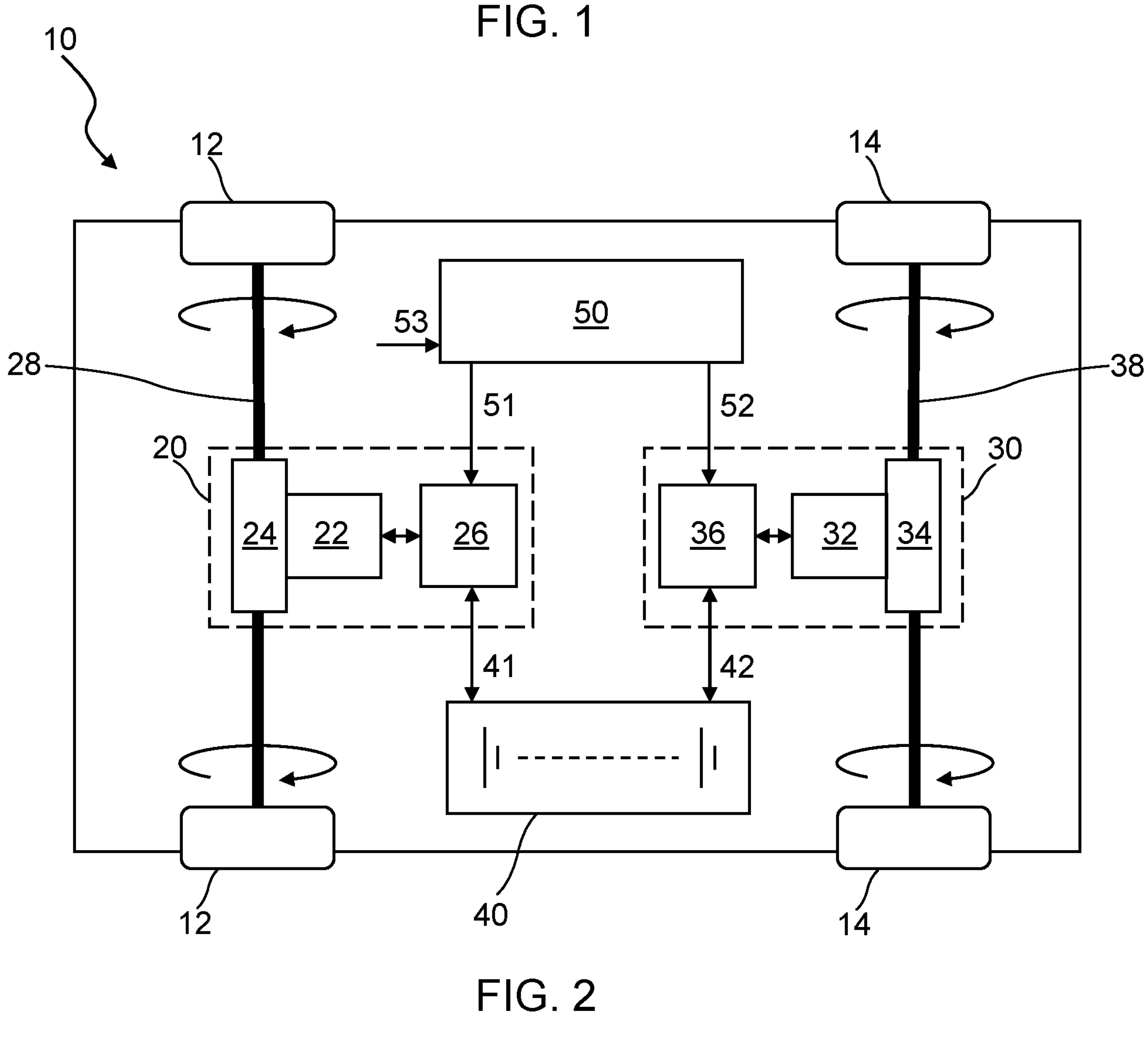
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FIG. 2

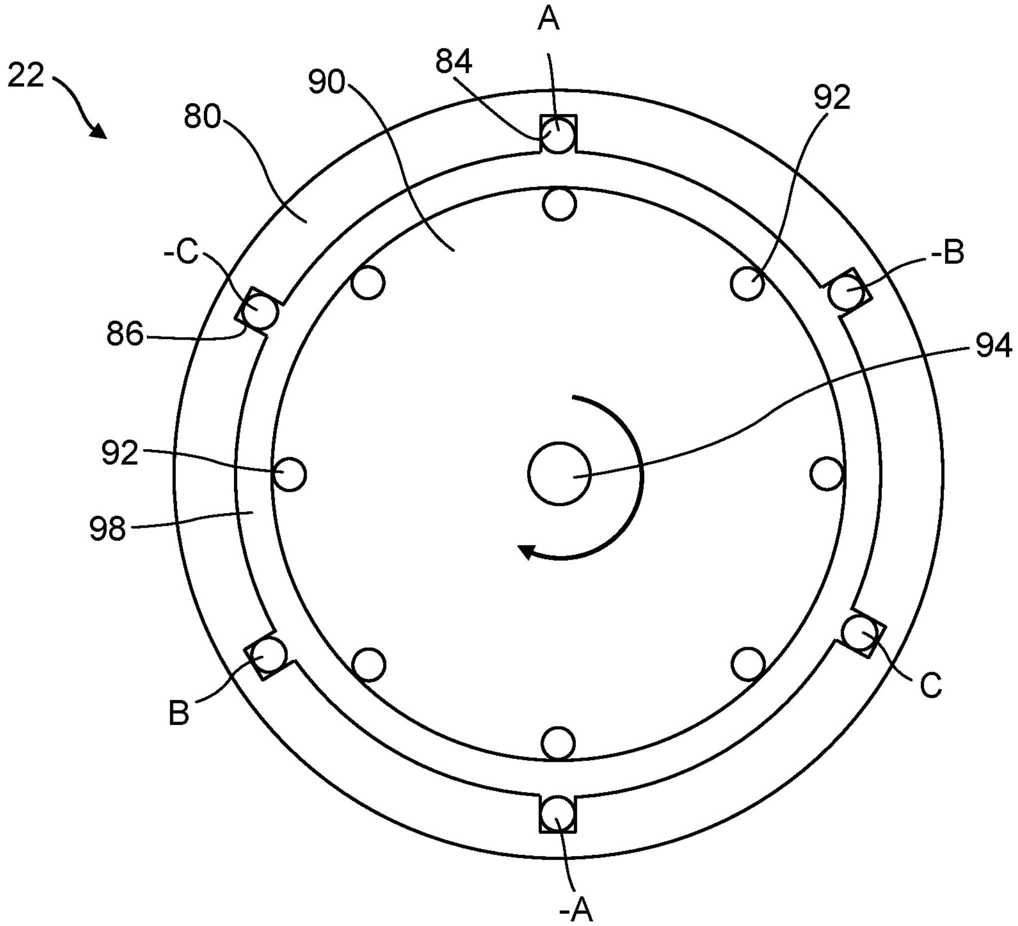

FIG. 3

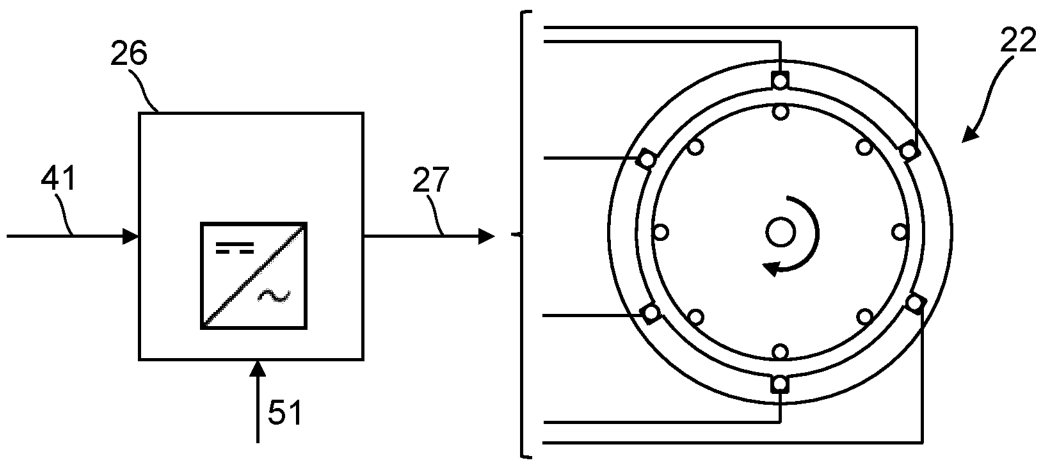

FIG. 4

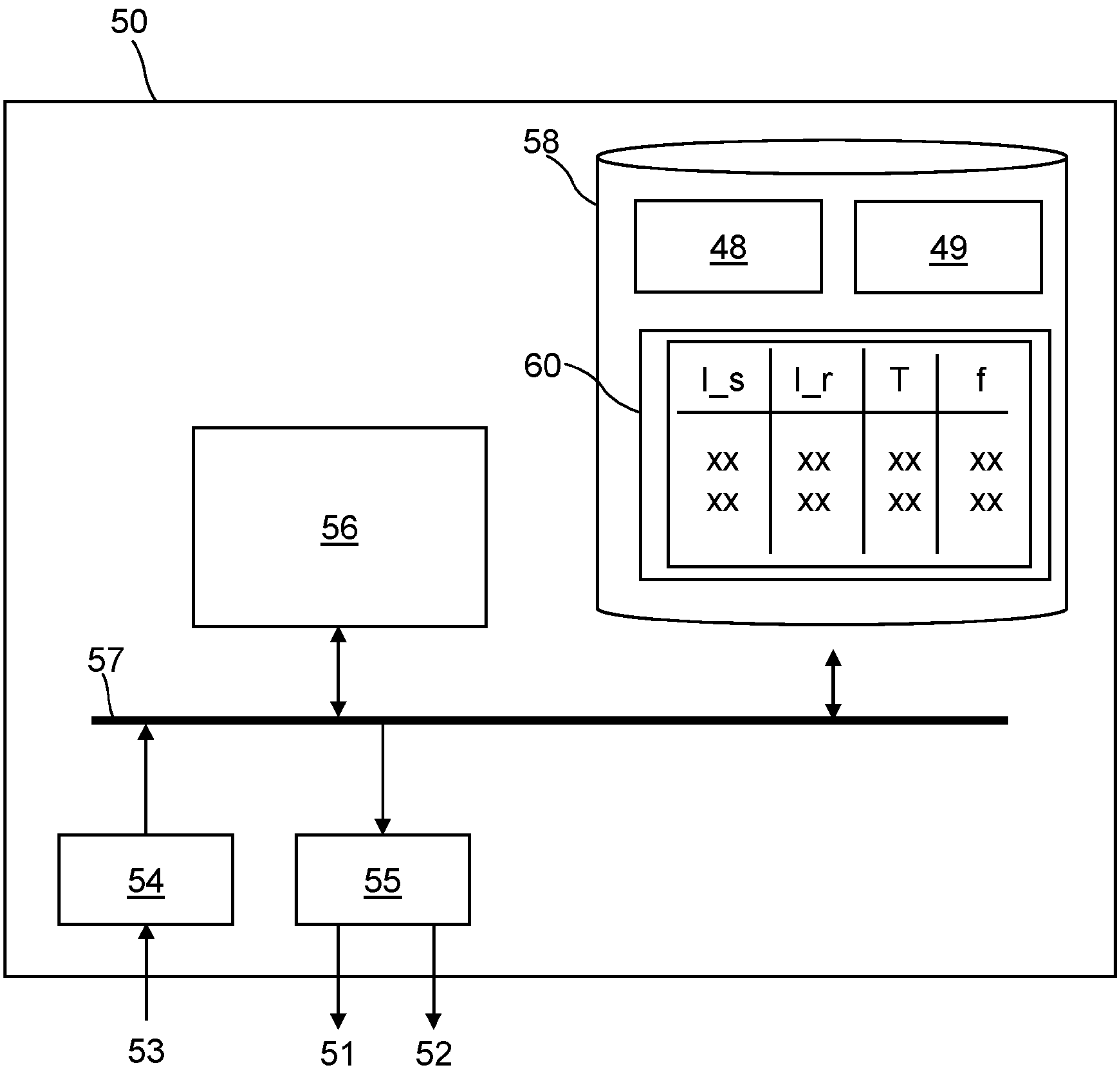

FIG. 5

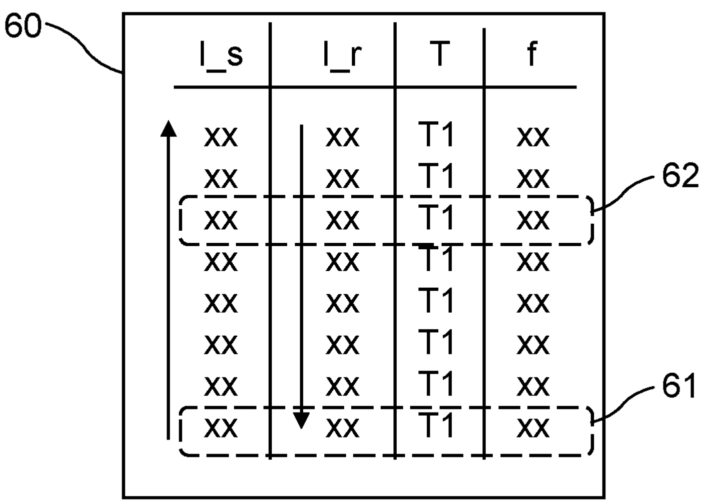

FIG. 6

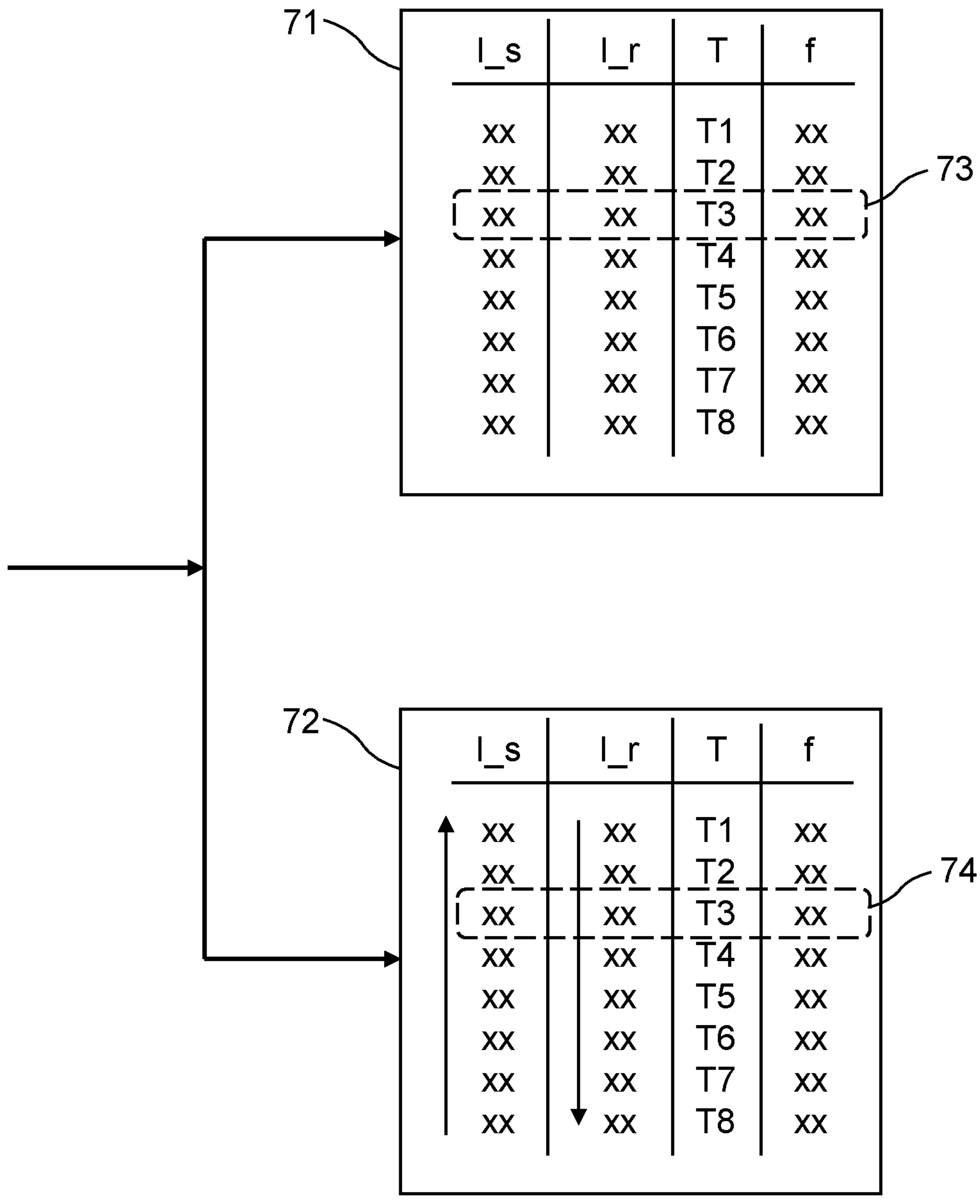

FIG. 7

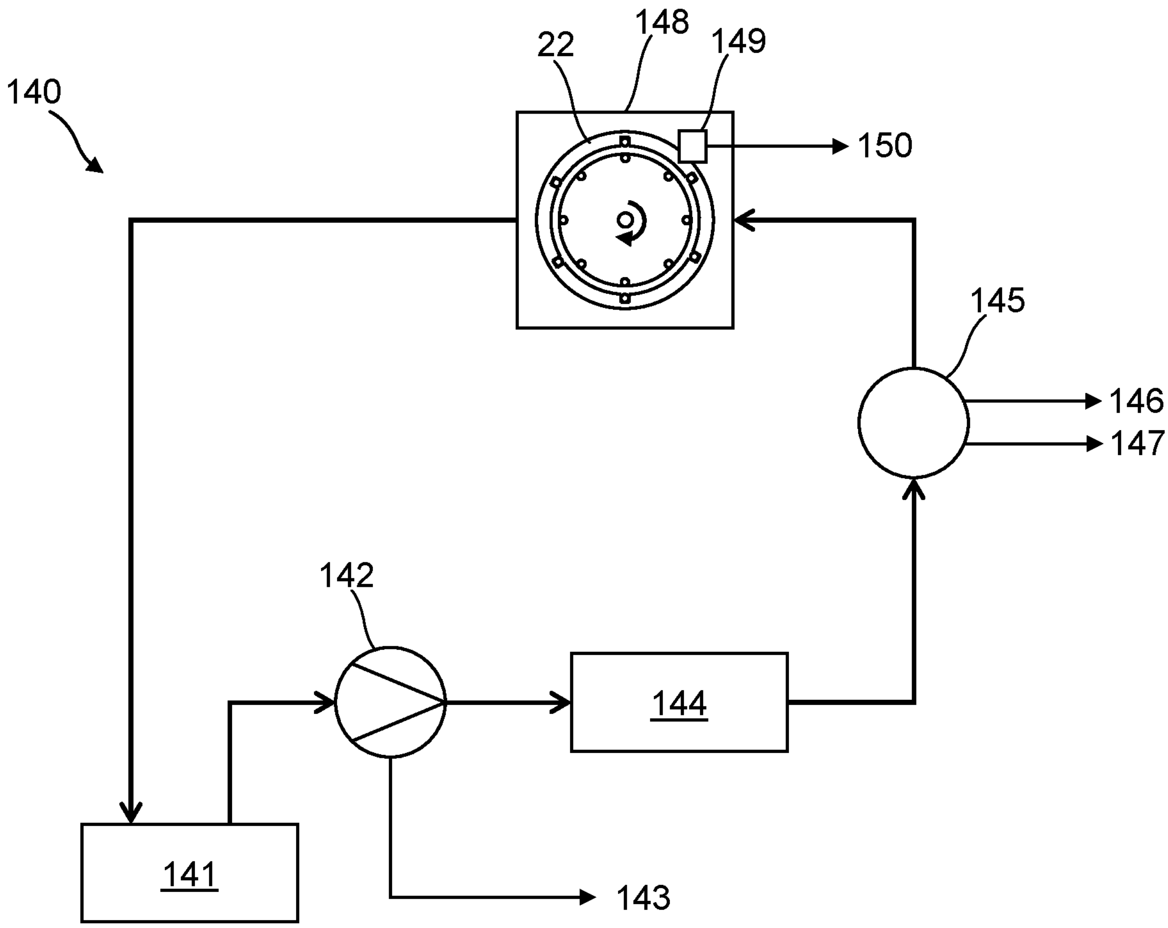

FIG. 8

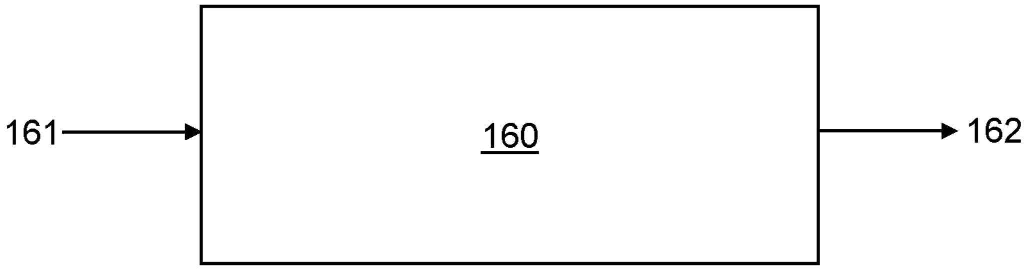

FIG. 9

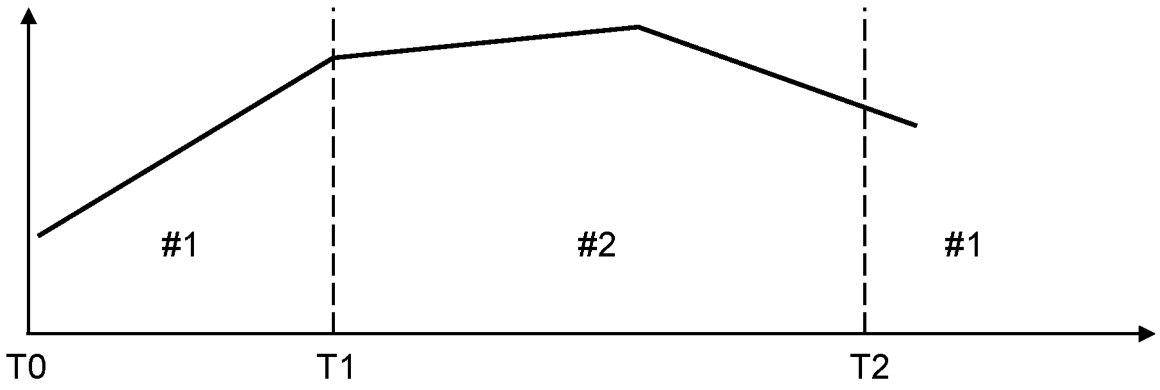

FIG. 10

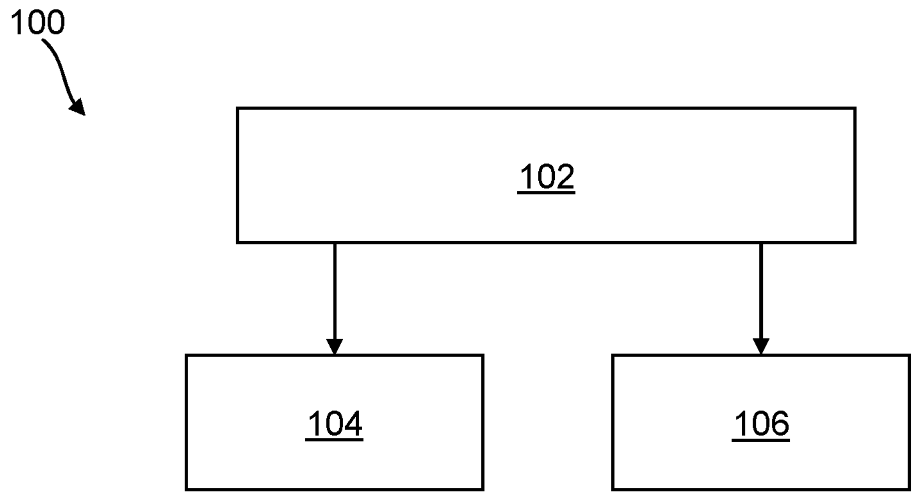

FIG. 11

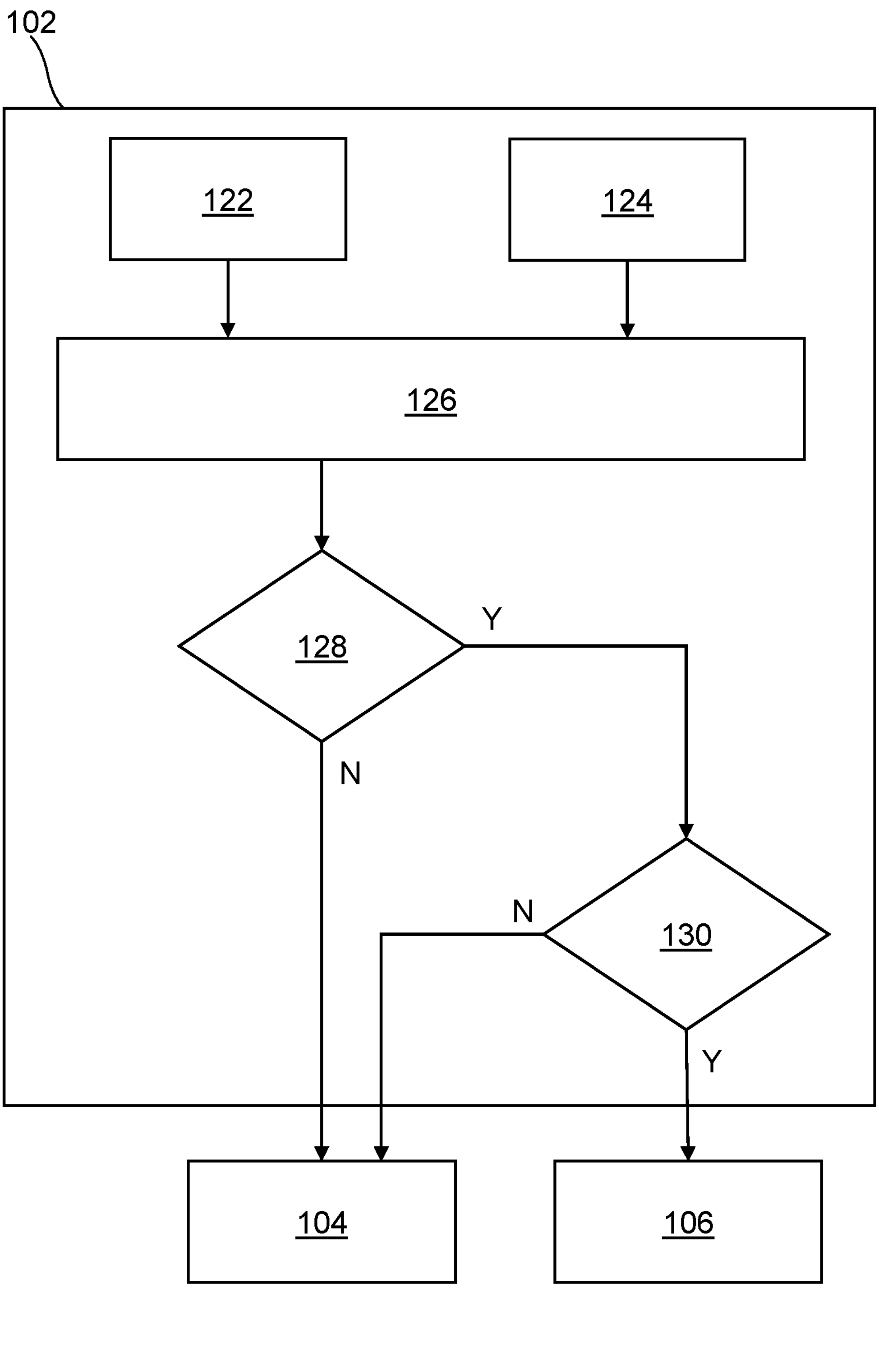

FIG. 12

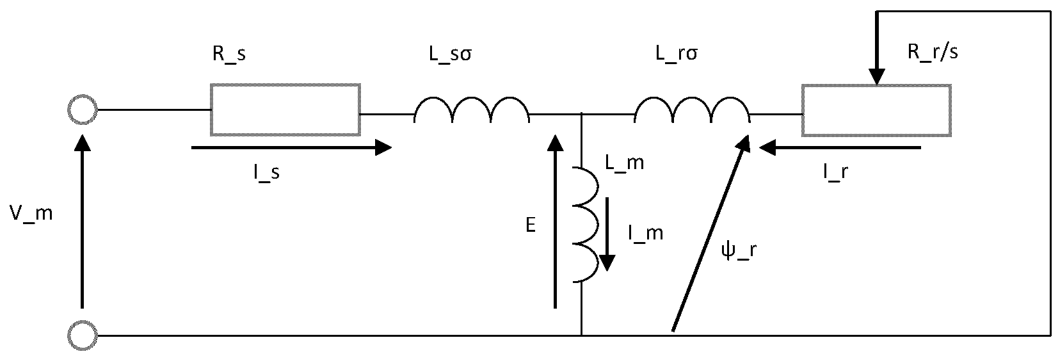
R_s
L_sσ
L_rσ
R_r/s
I_s
L_m
I_r
V_m
E
I_m
ψ_r

FIG. 13

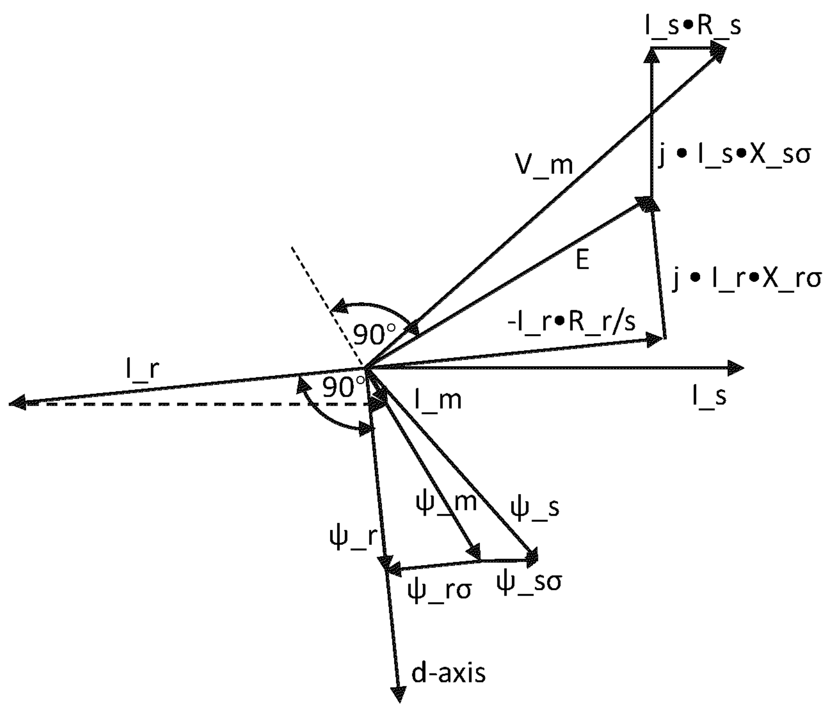
I_s•R_s
V_m
j • I_s•X_sσ
E
j • I_r•X_rσ
90°
-I_r•R_r/s
I_r
90°
I_m
I_s
ψ_m
ψ_s
ψ_r
ψ_rσ
ψ_sσ
d-axis

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/069077

A. CLASSIFICATION OF SUBJECT MATTER
INV. B60L3/00 B60L15/02 B60L15/20 H02P5/46 H02P5/74
H02P27/04 H02P29/66 H02P29/032
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B60L H02P

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/242272 A1 (YAMADA EIJI [JP] ET AL) 27 September 2012 (2012-09-27) figures 1-8 paragraphs [0025], [0041] - [0069] -----	1-15
X	EP 4 002 681 A1 (VALEO SIEMENS EAUTOMOTIVE GERMANY GMBH [DE]) 25 May 2022 (2022-05-25) figures 1-4 paragraphs [0020] - [0050] -----	1-15
A	US 2018/145624 A1 (KIM KYUNG SU [KR]) 24 May 2018 (2018-05-24) figures 1-4 paragraphs [0037] - [0074] -----	1-15
	-/--	

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 October 2024	14/10/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gücin, Taha

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Form PCT/ISA/210 (second sheet) (April 2005)

International application No
PCT/EP2024/069077

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2009/284202 A1 (MIURA TETSUYA [JP]) 19 November 2009 (2009-11-19) figures 1-7 paragraphs [0018] - [0049] -----	1-15

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International application No
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