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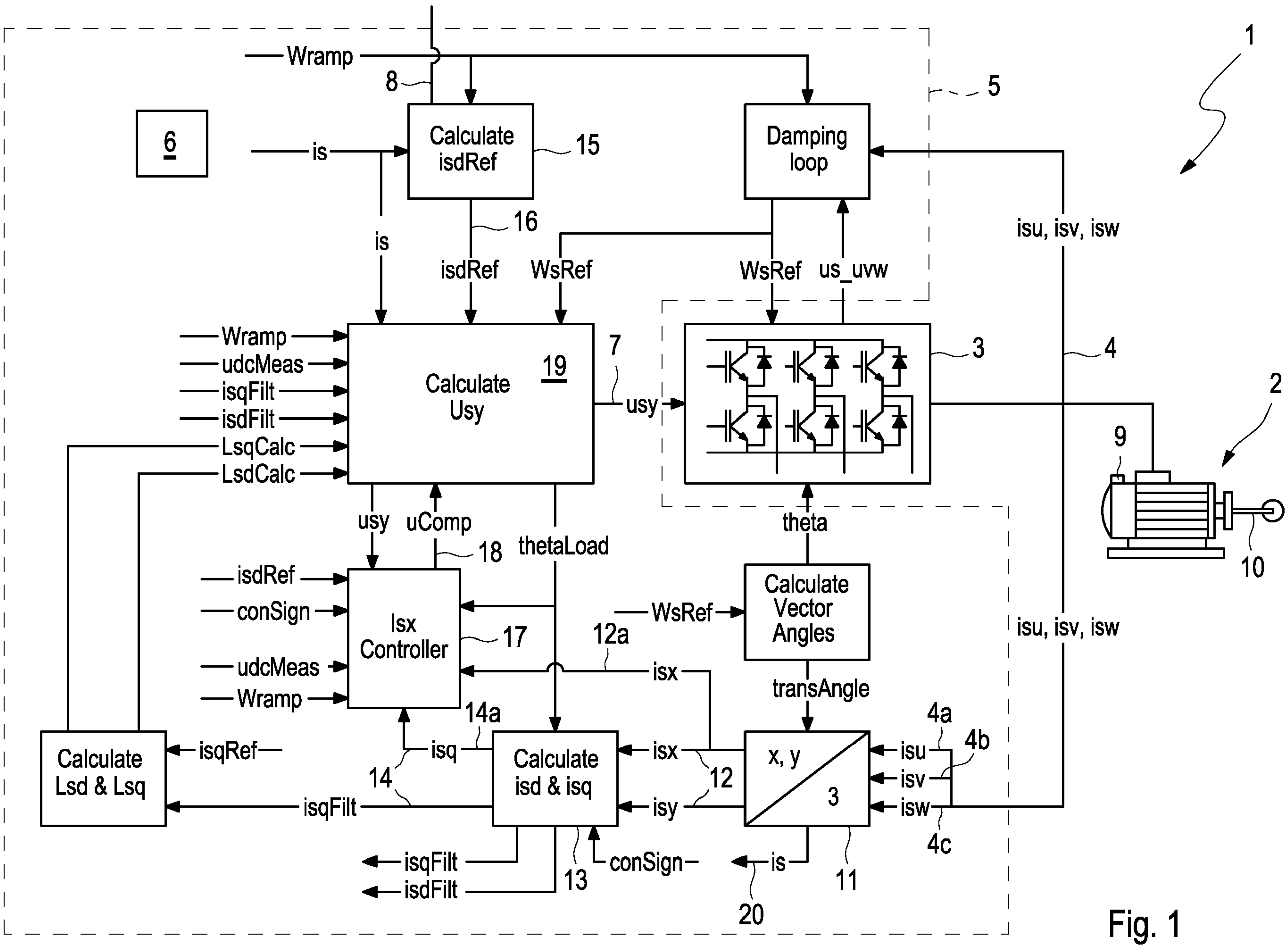

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Fig. 1

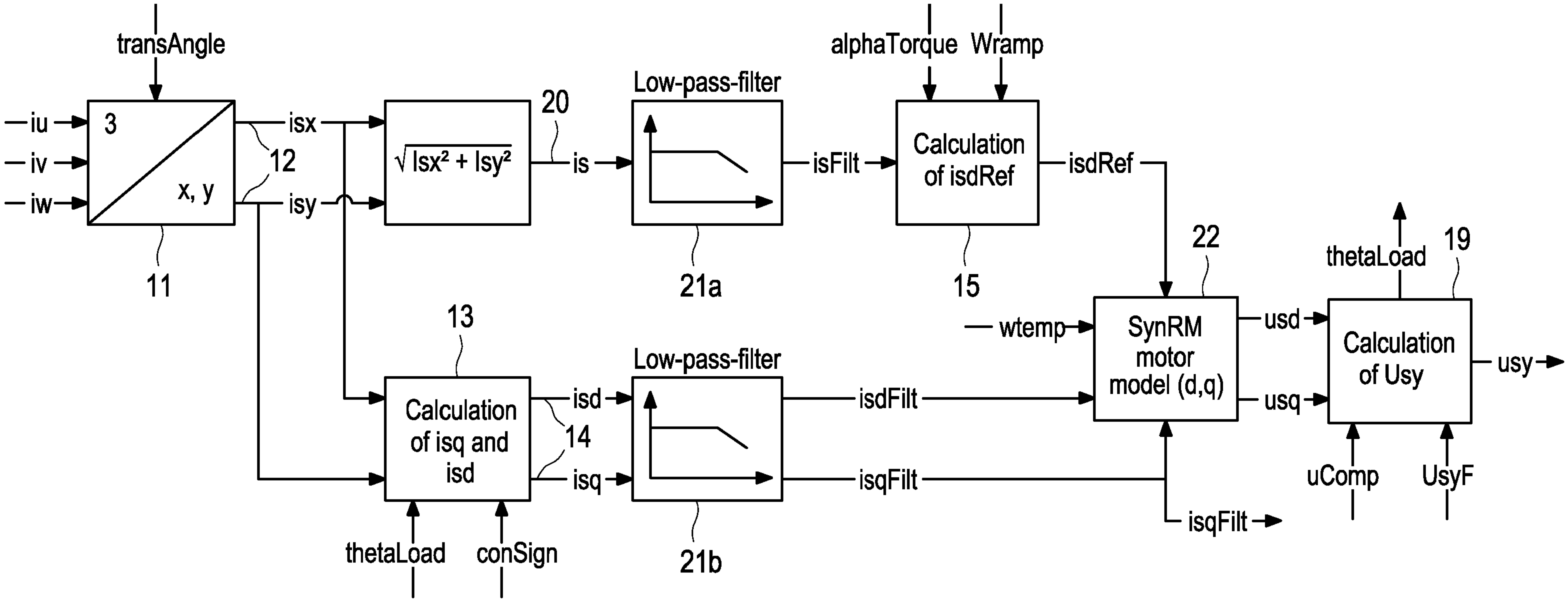
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Fig. 2

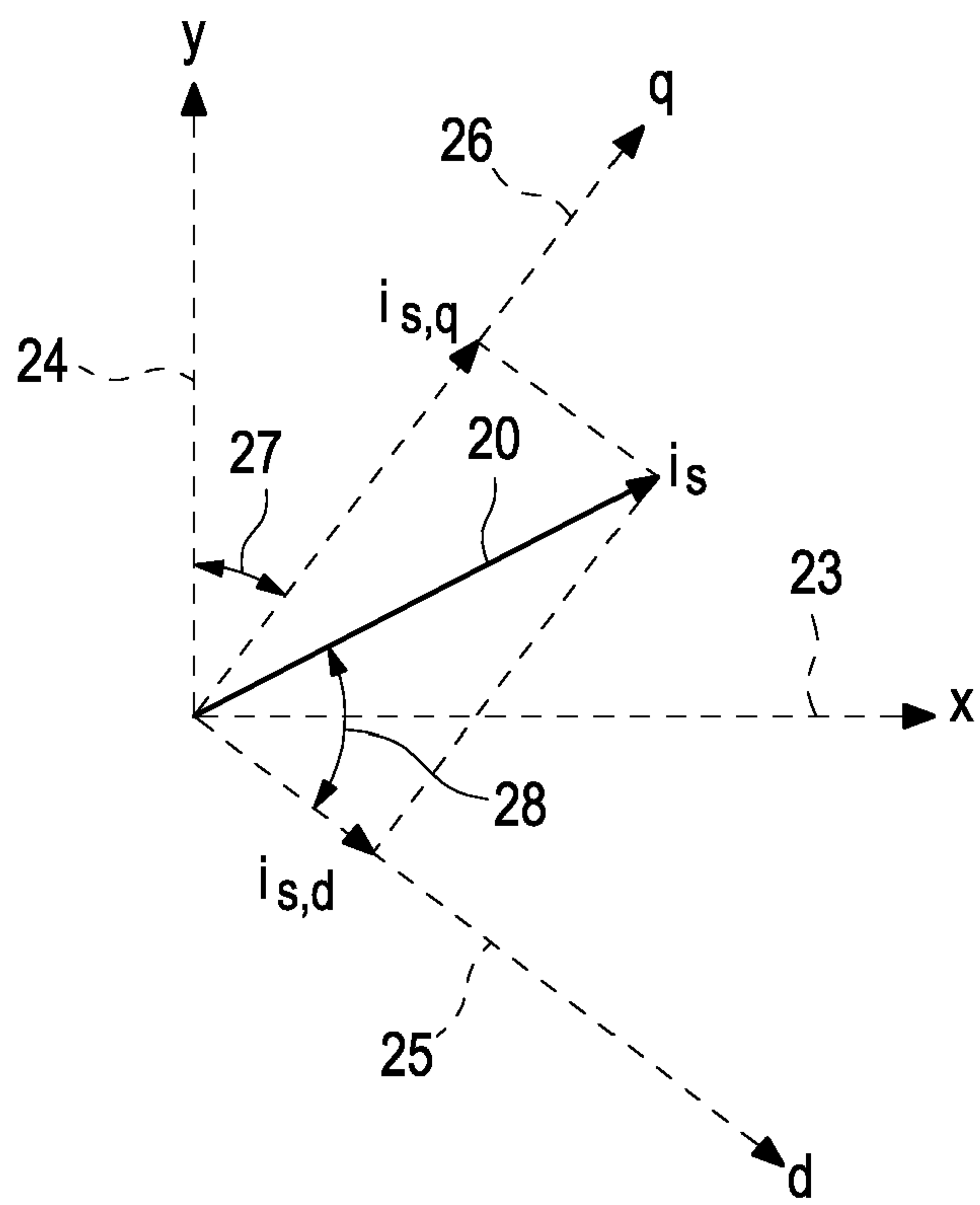

Fig. 3

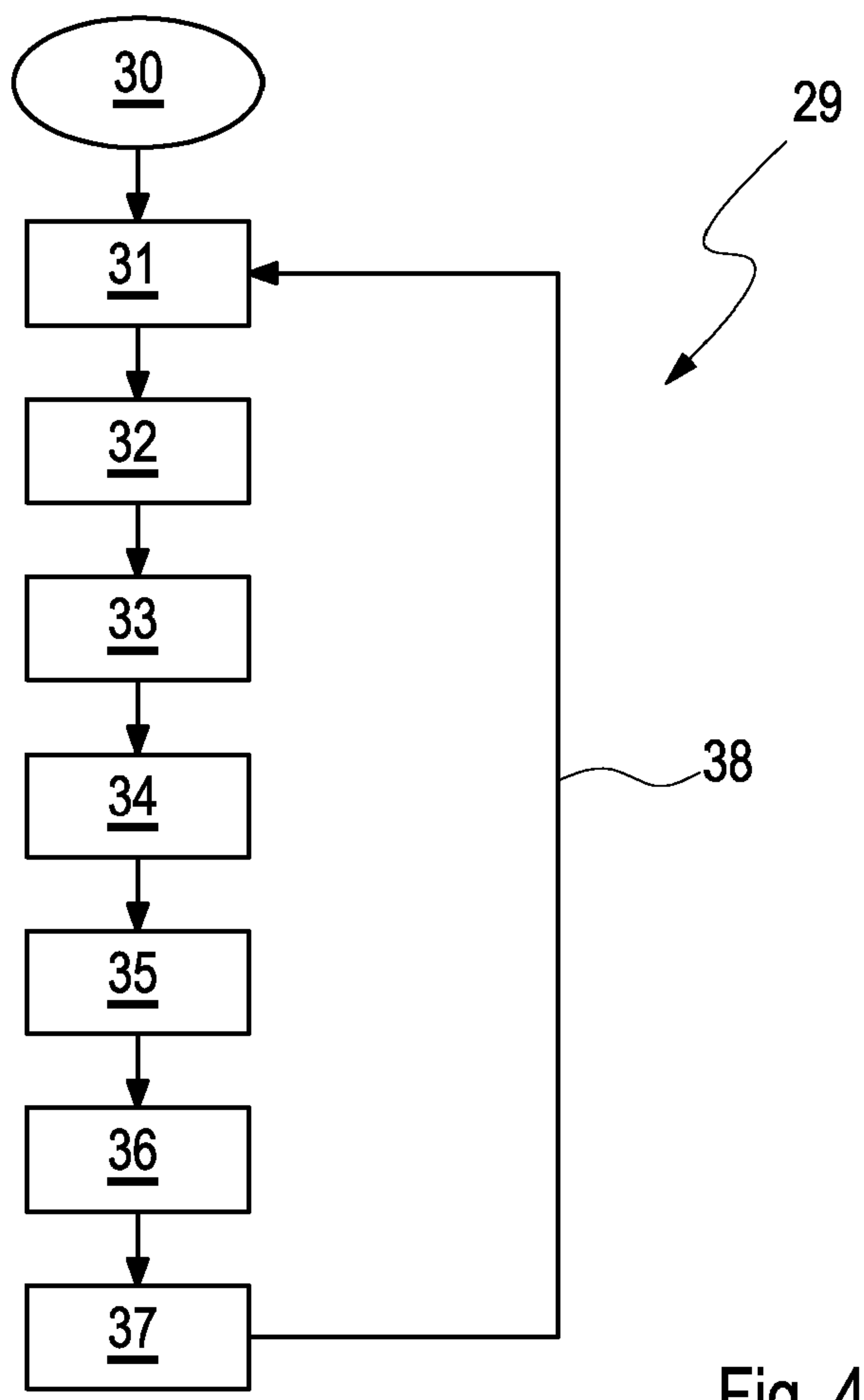

Fig. 4

METHOD FOR CONTROLLING A SYNCHRONOUS RELUCTANCE ELECTRIC MOTOR

FIELD OF THE INVENTION

The invention relates to a method for controlling a synchronous reluctance electric motor or permanent magnet assisted synchronous reluctance electric motor, wherein at least one electric voltage that is applied to the synchronous reluctance electric motor is controlled. Additionally, the invention relates to a controller unit for controlling a permanent magnet assisted synchronous reluctance electric motor or a synchronous reluctance electric motor. Furthermore, the invention relates to an electric motor unit.

BACKGROUND TO THE INVENTION

Electric motors are nowadays employed for a plethora of different applications in essentially all fields of technology. Depending on the actual use of the respective electric motor, various types and various sizes of electric motors are employed.

As an example, if an electric motor has to be used for an application where a constant turning speed of the electric motor can be used or is even required, a synchronous electric motor without a commutator can be used, in particular if alternating current is available. However, a start-up of such an electric motor might be difficult if a load with a large moment of inertia has to be driven.

If, however, a variable turning speed of the electric motor has to be provided (and additionally in the case of a direct current source), the traditional approach was to use electric motors, comprising a commutator (so called asynchronous electric motors). A problem involved with such commutated electric machines is the commutator, since this is a component that is particularly subject to a non-negligible wear. Furthermore, when using a commutator, typically sparks occur when the electric motor is turning. Such sparks can render the resulting electric motor unusable for certain applications, in particular if flammable gases are around, unless additional precautions are taken.

With the advent of modern semiconductor-based power electronics, the use of synchronous electric motors, in particular synchronous reluctance electric motors, has become more and more widespread. With such synchronous electric motors, commutators can be dispensed with. Furthermore, by providing an alternating electric current with a variable frequency, a synchronous electric motor can be driven at essentially any rotating speed. Even changes in turning speed can be realised. This has made possible certain applications that were hard to achieve, if at all, beforehand.

With the increasing number of electric motors there is an increasing interest for simple methods for controlling electric motors. This is because this way the necessary electronics for controlling the electric motors can become simpler and hence smaller, less energy consuming, more reliable and in particular less costly.

Although a number of different controllers for electric motors and a variety of methods for driving electric motors are known in the state of the art, there is still a desire for further improvements.

It is therefore the object of the invention to provide a method for controlling a synchronous reluctance electric motor that is improved over presently known methods for controlling a synchronous reluctance electric motor. It is another object of the invention to provide a controller unit for controlling a synchronous reluctance electric motor that is improved over presently known controller units for controlling a synchronous reluctance electric motor. Yet another object of the invention is to provide an electric motor unit that is improved over electric controller units according to the state of the art.

The presently proposed invention seeks to address these objects.

SUMMARY OF THE INVENTION

In accordance with an aspect of the invention there is provided a method for controlling a synchronous reluctance electric motor or a permanent magnet assisted synchronous reluctance electric motor, wherein the method comprises applying at least one electric voltage to an inverter unit to drive the motor; measuring an electric current provided to the motor (2); converting the measured electric current to a d-q reference frame, wherein the measured electric current is first transformed into an x-y-reference frame; controlling the at least one electric voltage (7) on the basis of the converted electric current in the d-q reference frame The d-q-reference frame is usually the reference frame of the rotating rotor that is connected to the shaft of the electric motor. Therefore it can be considered to be some kind of a "rotating mechanical reference frame". It is usually not identical to the rotating magnetic field system of the stator (which is typically referred to as the so-called stator reference frame and/or the x-y-reference frame), in particular if a load is imposed on the electric motor. Typically, if the load to the electric motor is increased, the angle between the d-q-reference frame and the x-y-reference frame will increase. Typically, once an angle of 90° between the d-q-reference frame and the x-y-reference frame is exceeded, a normal mechanical rotation of the electric motor cannot be sustained. The electric voltage is preferably controlled vectorially, i.e. both its magnitude and its direction are controlled (vector parameter). Preferably, the control is performed essentially during the majority of the time (or essentially all the time) based on said at least one electric current. However, it can be preferred if an exception to this general rule is foreseen in the case of "unusual" situations like an emergency shut-down operation, during missing control input or the like. First experiments have shown that using the suggested method, a very efficient control of a synchronous reluctance electric motor can be realised with a very simple algorithm. In particular, it is even possible to essentially perform the control of the synchronous reluctance electric motor by measuring and calculating a single value, comparing it to a single reference value and to generate an appropriate output signal. By a "value", a vectorial value and/or a single parameter is encompassed. A vector can comprise several dimensions, in particular two, three, four, five, six or more dimensions. Consequently, any means for implementing the suggested method can be accordingly simple.

Preferably, the method is employed in a way that said converted electric current is the electric current in the d-direction. The d-axis of the d-q-reference frame is typically defined as the fraction of the applied electric current that is the cause for creating the magnetic field (magnetising current), while the q-direction of the d-q-reference frame is the part of the electric current that is producing the generated torque (torque producing current). First experiments have shown that an electric current in the d-direction is particularly useful for implementing a method for controlling a synchronous reluctance electric motor.

According to a preferred embodiment of the invention, the method is performed in a way that said converted electric current is compared to at least one reference value. This comparison can be both performed with respect to a single parameter (like the magnitude of an electric current or the angle of an electric current), with respect to a combination of two or more parameters and/or with respect to one or more vectors (like a vectorial electric current, as an example; wherein the dimension of the vector can be two, three, four, five, six or higher and/or a plurality of vectors can be used). First experiments have shown that such a comparison can be performed comparatively easy and that the result of such a comparison is usually very suitable for controlling a synchronous reluctance electric motor, at least as a "starting point" for further calculations. The reference value can be fixed or can be varied depending on working conditions and/or external parameters (including user commands). As examples for working conditions, a temperature, a required torque, mechanical limitations of the electric motor and/or components that are connected to the electric motor, power consumption limitations, turning speed of the electric motor or the like can be used.

It is furthermore possible that the method is performed in a way that essentially a single electric current is used for determining said electric voltage. Using such a preferred embodiment, the control algorithm can usually be particularly simple. Therefore, the means for implementing such a method can typically be correspondingly simple. Nevertheless, as first experiments have indicated, the control of the synchronous reluctance electric motor can be performed in a very suitable way.

Even more preferred, it is suggested to perform the method in a way that said converted electric current is calculated from the measured electric currents through the synchronous reluctance electric motor that is controlled by the method. Using this preferred embodiment, usually a very good control can be performed with relatively little effort. In particular, usually the electric current through the electric motor has to be determined anyhow for performing a variety (if not all) control strategies. Therefore, the respective sensors are typically already present. Nevertheless, it should be mentioned that it is also possible that at least a part of the electric currents are determined from the actuation pattern (for example from a pulse width ratio, the electric voltage, changes in the electric parameters or the like). Usually, one, two or a relatively small number of electric currents are sufficient to perform a comparatively good control of the electric motor. As an example, if a three-phase electric motor is actuated as suggested, the electric current of a single phase, of two phases, of three phases and presumably additionally a star point electric current can be measured.

In particular the method is performed in a way that the measured electric current(s) are first transformed into a rotating reference frame (the x-y-system). This way, the control strategy (in particular a comparison between a current parameter/set of parameters and a reference parameter/set of reference parameters) can be performed particularly easily. It is to be noted that the measured electric current(s) is/are measured in a static reference frame. Typically, these electric current(s) is/are varying sinusoidally with time. The rotating reference system should preferably rotate with the same rotating speed as the rotor of the electric motor, at least as long as the working conditions (in particular the mechanical load imposed onto the electric motor) are not changed. Therefore, it is still possible that a "creeping change" between said rotating reference frame and the rotor of the electric motor can occur, in particular if working conditions change. This recalculation cannot be only done once, but even several times (as an example two times). In particular, additionally and/or alternatively, a re-calculation from one rotating reference frame into another rotating reference frame can be done. According to preferred embodiment, the external electric currents (varying periodically according to the turning speed of the electric motor) are first transformed into the x-y-reference frame and afterwards into the d-q-reference frame.

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Furthermore, the method can be performed in a way that the control of said at least one electric voltage is at least at times additionally based on at least one sensor signal and/or at least at times based on at least one control command. This way, the control of the electric motor can be even better adapted to user preferences and/or a required behaviour of the electric motor and/or to current working conditions of the electric motor. In particular, a sensor can be used for determining the temperature of the electric motor, its turning speed or the like.

Additionally, it is suggested to perform the method in a way that at least at times at least one damping loop is used. The damping loop uses a high-pass filter in order to modulate the supply frequency to the machine. This is provided to stabilize the machine since it is not generally possible to ramp-up a synchronous reluctance machine without this damping loop.

It is furthermore suggested to perform the method in a way that at least in part and/or at least at times at least one limiting function is applied, preferably at least one limiting function that limits at least one electric voltage and/or at least one electric current that is applied to the electric motor and/or at least one mechanical force that is generated. This way, it is possible that overload conditions are avoided and hence the reliability of the system can usually be improved. The limiting function can be even employed in a "two-step approach", meaning that, as an example, a certain limit may be exceeded under certain conditions and/or for a certain period of time, while a second limiting value comprises an "absolute value" that must never be exceeded. Using such a two-step approach, it is possible to optimise the resulting system even further. In particular, an unnecessarily large electric motor for working conditions that occur only very rarely can be avoided.

Another preferred embodiment of the method can be achieved if at least in part and/or at least at times at least one correcting function is applied that is correcting for non-linear behaviour of at least one electric and/or electronic component. This way, the overall control of the electric motor can be even more precise, resulting in an even more improved system. In particular, the correcting function can be modified according to the particular embodiment of the electric motor unit, the synchronous reluctance electric motor and/or the controller unit that is/are employed.

In accordance with another aspect of the invention there is provided a controller unit. Such a controller unit can be used for driving a synchronous reluctance electric motor. The resulting controller unit and/or the resulting synchronous reluctance electric motor, driven by the controller unit, can show the previously described features and advantages, at least in analogy. Also, variations and improvements according to the previous description can be employed for the controller unit as well, at least in analogy.

In particular, it is possible that the controller unit comprises at least one inverter unit. Such inverter units are typically used for changing a direct electric current into an alternating electric current (typically of a variable frequency). Also, such inverter units can be used for varying the frequency of an alternating electric current. In principle, the inverter unit can be of any design. For example, DIACs, TRIACs, thyristors, IGBTs, FETs, MOSFETs or the like can be used.

According to a preferred embodiment of the controller unit, at least one electric current measuring device, preferably an array of electric current measuring devices are used. This way, particularly precise values can be used as input parameters for the control of the electric motor. Typically, such electric current measuring devices are relatively inexpensive. The electric current measuring devices can be of essentially any design, in particular according to any design that is known in the state of the art.

Preferably, the controller unit comprises a programmable memory device. In the programmable memory device, a method according to the previous description can be stored.

Of course, the controller unit can be designed in a variety of ways. In particular, a partially analog and/or a partially digital design is possible. In particular, programmable computer devices (for example single-board computers) can be employed for this purpose.

In accordance with another aspect of the invention there is provided an electric motor unit. Such an electric motor unit can show the same features and advantages as previously described, at least in analogy. Furthermore, such an electric motor unit can be modified according to the previous description as well, at least in analogy.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention and its advantages will become more apparent, when looking at the following description of possible embodiments of the invention, which will be described with reference to the accompanying figures, which are showing:

Fig. 1: a block diagram of a possible embodiment of an electric motor unit;
Fig. 2: a more detailed block diagram of a part of a possible embodiment for the calculation of the voltage vector;

Fig. 3: a vector diagram showing the relation between the different vectors in the different reference systems;

Fig. 4: a possible embodiment of a method for controlling an electric motor.

DETAILED DESCRIPTION OF THE INVENTION

In Fig. 1 a schematic block diagram of a possible embodiment of an electric motor unit 1 is shown. The electric motor unit 1 of the presently shown embodiment comprises an electric motor 2 of a synchronous reluctance motor design (synchronous reluctance machine or a permanent magnet assisted synchronous reluctance electric motor). The electric motor 2 is electrically driven by an inverter unit 3 that is used to provide the electric motor 2 with an electric current 4 of a variable frequency. In the presently shown embodiment, the electric current 4 that is used for driving the electric motor 2 (and hence the electric current 4 that is provided by the inverter unit 3) is of a three-phase type. In the presently shown embodiment, the inverter unit 3 generates the electric current 4 out of a direct electric current (direct current source not shown in Fig. 1).

The control of the inverter unit 3 is performed by an electronic controller unit 5 that is of a single-board computer type in the presently shown embodiment. Within the block, representing the electronic controller unit 5, another block is indicated that represents an electronic memory 6 in which a program for the actuation of the electric motor 2 via the inverter unit 3 is stored.

It is to be understood that the electric current 4 that is going through the electric motor 2 is not directly controlled by the electronic controller unit 5 and/or the electric inverter unit 3. Instead, a vectorial value for the driving voltage vector 7 is the value that is directly controlled. This value is the output value (voltage vector 7) of the electronic controller unit 5 and hence the input value of the inverter unit 3. The electric current 4 (in particular the presently three phases u, v, w of the electric current 4) contains some "response function" of the electric motor 2, already. Therefore, the electric current 4 can be measured and used as the (usually) main input value of the electronic controller unit 5. Additionally, a user input line 8 is indicated in Fig. 1. This user input line 8 can be used for requesting a certain turning speed or the like. Furthermore some sensors 9 can be foreseen (only schematically indicated in Fig. 1) for collecting additional data. As an example, a sensor 9 can probe for a temperature, the mechanical position of the rotor, the turning speed of the rotor 10 or the like. It is to be understood, however, that according to the presently proposed invention the sole use of the electric current 4 is sufficient for realising the required control of the electric motor 2 and so the sensors 9 are typically omitted. The electric motor unit 1 (in particular the electronic controller unit 5) can hence be simple, small and relatively inexpensive.

The measured electric current 4 (where the measurement can be done by current sensors that are presently not indicated) forms the "main" data input source for the electronic controller unit 5. The measured electric current 4 (that is measured in a stationary reference frame and hence varies with time; typically with a sinusoidal shape) is first transformed into the x-y-system (x-y-reference frame; see also Fig. 3). The x-y-system corresponds to the rotating magnetic field that is created by the stator of the electric motor 2. The x-y-system will rotate with the rotating frequency ω of the driving shaft 10/rotor of the electric motor 2. Because the x-y-system rotates together with the rotor of the electric motor 2, the output currents 12 i_{sx} and i_{sy} are relatively constant with time. In particular, they do not vary with the rotating frequency of the electric motor 2. However, changes that are due to a different rotating speed, a different load on the electric motor 2 or the like are of course still possible.

The calculated electric currents i_{sx}, i_{sy} 12 in the x-y-system are passed on to the next logic block 13, where the electric currents are recalculated another time into the d-q-system (see also Fig. 3). The d-q-system (d-q-reference frame) rotates with the same frequency ω as the x-y-system and hence as the rotor of the electric motor. However, if a load is applied to the rotating shaft 10 of the electric motor 2, a shift between the x-y-system and the d-q-system will usually occur. This shift will manifest itself in form of the so-called load angle 27. This will be further elucidated with respect to Fig. 3. Now, we have the electric current 14 (including its various components) in the d-q-system.

In parallel, the measured overall stator current i_s is used and compared with the various user inputs 8. From this, the commanded referencing stator current isdRef 16 is calculated in the isdRef calculation block 15. The stator current i_s is a vector formed of a q-axis component (i_q) and a d-axis component (i_d). The angle of the vector relative to the d-axis is the torque angle 28 (see Fig. 3).

The value of the commanded reference current 16 is one of the three major input parameters for the stator current controller box 17. The other two crucial parameters are the fraction of the stator current parallel to the x-axis in the x-y-system i_{sx} 12a and the fraction of the stator current parallel to the q-axis in the d-q-system i_{sq} 14a, as can be seen in Fig. 1. The stator current control box 17 calculates a stator current in x-direction that should be present and compares it with the measured stator current in the x-direction i_{sx} 12a. The discrepancy between the calculated and the fraction of the measured stator current in x-direction is used to create a voltage error term

u_{Comp} 18 that is the main output of the stator current control box 17. This error voltage 18 is used as an input for the voltage vector control box 19, where the voltage vector u_{sy} 7 is calculated. This calculated value of the voltage vector 7 is transferred to the electric inverter unit 3 that is used for driving the electric motor 2.

In Fig. 2 a more detailed drawing of the preparation of the various signals is shown. In particular, one has to realise that some more steps in between are preferably performed. In particular, the various measured and calculated currents 12, 14, 20 are first passed through low-pass filters 21a, 21b before they are used for further processing. This is important, because otherwise electric noise that is generated by the inverter unit 3 of the electric motor unit 1 itself could significantly disturb the control loop and hence lead to unwanted fluctuations and an unwanted behaviour of the electric motor 2.

Yet another modification is indicated in Fig. 2. This is the modifying block 22 in which the voltages u_{sd} and u_{sq} are calculated from a steady-state synchronous reluctance machine motor model in the d-q-system. By using this modification block 22 dead times and/or voltage drops for the various semiconductor components are taken into account for the calculation of the voltage vector 7. First experiments have shown that by using this modification block 22 in particular the low speed performance of the electric motor 2 can be improved.

In Fig. 3 the various reference frames and some of the (vectorial) parameters are illustrated. The x-y-system (x-y-reference frame) is spanned by the x-axis 23 and the y-axis 24. The x-y-system represents the coordinate system of the rotating magnetic field that is created by the stator of the electric motor 2.

The d-q-system (d-q-reference frame) is spanned by the d-axis 25 and the q-axis 26. The d-q-system also rotates with the same frequency ω as the x-y-system. However, if a load is applied to the rotating shaft 10 of the electric motor 2, a shift between the x-y-system and the d-q-system will occur. The shift will manifest itself in form of the so-called load angle 27 (the angle between the y-axis 24 and the q-axis 26).

In Fig. 4, a schematic overview of a possible embodiment of a method for actuating an electric motor 2 is shown in form of a flowchart 29. First of all, the algorithm starts with a start-up step 30. During the start-up step 30, various parameters can be read in, in particular some design parameters of the electric motor 2 or other components of the electric motor unit 1. This data can be read out of an electronic memory 6, for example.

Then the current electric current is measured in step 31. The measured current (more exactly: the three phases u, v, w of the electric current 4) is transformed into the x-y-system in first transformation step 32. Hence, one obtains the i_{sx} and i_{sy} currents 12.

Then, the stator current reference value in the d-direction isdRef 16 is calculated in the stator current calculation step 33.

After this, a filter function is applied to the various calculated and measured values in filtering step 34.

After this, the damping function is applied in damping step 35.

Hence, the error signal of the driving voltage u_{Comp} 18 is calculated in the error voltage calculation step 36. Based on this, the driving voltage vector 7 is calculated in voltage vector calculation step 37. This refers both to the magnitude of the voltage vector 7, as well as to its direction (voltage vector angle).

After this the loop is closed by a step-back function 38.

Additional information can be taken from another application with the title "Variable torque angle for electric motor" that has been filed on the very same day by the same applicant and having the UK Patent Application publication number GB2503040. The content of that application is incorporated in full into the present application.

The embodiments of the invention described above are provided by way of example only. The skilled person will be aware of many modifications, changes and substitutions that could be made without departing from the scope of the present invention. The claims of the present invention are intended to cover all such modifications, changes and substitutions as fall within the scope of the invention.

Reference list

1. electric motor unit
2. electric motor
3. inverter unit
4. electric current
5. electronic controller unit
6. electronic memory
7. voltage vector
8. user input line
9. sensors
10. rotor
11. transformation into a x-y-system
12. i_{sx}, i_{sy}
13. transformation into a d-q-system
14. current in q-direction isq
15. calculation of 16
16. stator current reference value in d-direction isdRef
17. stator current control box
18. error voltage u_{Comp}
19. voltage vector control box
20. stator current i_s
21. low-pass filter
22. modification block
23. x-axis
24. y-axis
25. d-axis
26. q-axis
27. load angle
28. torque angle
29. flowchart
30. start-up step
31. current measuring step
32. first transformation step
33. stator current calculation step
34. filtering step
35. damping function
36. error voltage calculation step
37. voltage vector calculation step
38. step-back

CLAIMS:

1. A method (29) for controlling a synchronous reluctance electric motor (2), the method comprising:

applying at least one electric voltage (7) to an inverter unit to drive the motor (2);

measuring an electric current provided to the motor (2);

converting the measured electric current to a d-q reference frame, wherein the measured electric current is first transformed into an x-y-reference frame;

controlling the at least one electric voltage (7) on the basis of the converted electric current in the d-q reference frame.

2. A method (29) according to claim 1, characterised in that said at least one electric voltage is controlled on the basis of the converted electric current in the d-direction (26).

3. A method (29) according to claim 1 or 2, characterised in that said converted electric current is compared to at least one reference value (16).

4. A method (29) according to any of the preceding claims, characterised in that essentially a single electric current is used for determining said electric voltage (7).

5. A method (29) according to any of the preceding claims, characterised in that the control of said at least one electric voltage (7) is at least at times additionally based on at least one sensor signal (9) and/or at least at times based on at least one control command (8).

6. A method (29) according to any of the preceding claims, characterised in that at least in part and/or at least at times at least one damping loop is used.

7. A method (29) according to any of the preceding claims, characterised in that at least in part and/or at least at times at least one limiting function is applied, preferably at least one limiting function that limits at least one electric voltage (7) and/or at least one electric current (4) that is applied to the synchronous reluctance electric motor (2) and/or at least a mechanical force that is generated.

8. A method (29) according to any of the preceding claims, characterised in that at least in part and/or at least at times at least one correcting function (22) is applied that is correcting for non-linear behaviour of at least one electric and/or electronic component (3).

9. A controller unit (5) configured to perform a method (29) according to any preceding claims.

10. An electric motor unit (1) configured to perform a method (29) according to any of claims 1 to 8.