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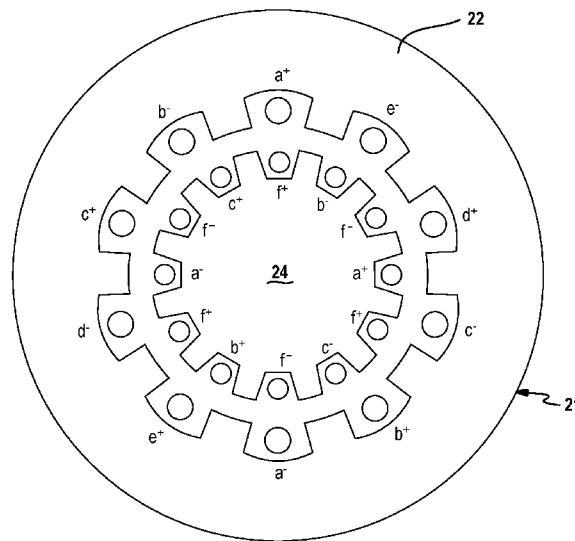
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(54) Title: BRUSHLESS, SELF-EXCITED SYNCHRONOUS FIELD-WINDING MACHINE



**FIG. 2A**

(57) Abstract: A brushless, self-excited synchronous field winding machine is presented. The AC stator is configured with four or more phases to produce independent magnetic fields at different spatial harmonics. Windings in the rotor are configured to magnetically couple to the different spatial harmonics produced by the AC stator. More specifically, an oscillating field generated by the stator magnetically couples to the excitation winding on the rotor. This induces an AC voltage which results in current flowing through the field winding of the rotor. The magnitude of the field current is therefore controlled by the magnitude of the oscillating field. The AC stator also produces a magnetic field at a different spatial harmonic which magnetically couples to field winding of the rotor. This component will interact with the field current to produce torque. With this approach, the power density of the electric machine is significantly increased as compared to conventional field winding designs.



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## BRUSHLESS, SELF-EXCITED SYNCHRONOUS FIELD-WINDING MACHINE

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims priority to U.S. Patent Application No. 16/385,556, filed on April 16, 2019, which claims the benefit of U.S. Provisional Application No. 62/658,850, filed on April 17, 2018. The entire disclosures of the above applications are incorporated herein by reference.

## FIELD

**[0002]** The present disclosure relates to synchronous field-winding electric machines.

## BACKGROUND

**[0003]** Electric machines used in variable speed drive applications such as the propulsion of hybrid electric vehicles should possess low cost and high power density. There are four electric machine topologies typically used in variable speed drives: induction, reluctance, permanent magnet (PM), and synchronous field winding. These fundamental topologies can be combined. A key example is the interior permanent magnet (IPM) machine, which combines the reluctance and permanent magnet topologies.

**[0004]** Permanent magnet and field-winding machines differ from induction and reluctance machines in that the rotor of the machine has an independent magnetic excitation. This allows these topologies to have higher torque densities. For example, under certain simplifying assumptions (e.g., linear magnetic behavior) it can be shown that a synchronous field-winding machine can produce 30% higher torque than an induction machine for a given amount of  $I^2R$  losses in the stator and rotor. Conversely, for a given torque, the field winding machine generates 30% less conduction losses than an induction machine.

**[0005]** Permanent magnet and field winding machines are also both capable of achieving unity power factor, unlike induction and reluctance machines where a maximum power factor of 0.8 is common. In variable-speed drive (VSD) applications, unity power factor means that the VSD can provide its peak power capability (based

upon its voltage and current constraints) to the machine. For a given power rating of the machine, this results in a reduced cost of the VSD, as transistors with lower current and/or voltage ratings can be used.

5       **[0006]** Finally, the independent excitation of synchronous field winding and certain permanent magnet machine designs allows these machines to achieve Constant Power over a Wide Speed Range (CPWSR). As a result of the existing machine topologies, permanent magnet and field-winding machines stand out as the most desirable.

10       **[0007]** Permanent magnet machines with rare earth magnets have been the topology of choice in high-performance applications, as the magnets generate magnetic fields without the conduction losses of field windings. However, the cost of rare earth materials has experienced high volatility, spurring interest in the development of  
15 alternative technologies.

**[0008]** The operation of synchronous field winding machines is similar to that of permanent magnet machines, except that electromagnets instead of permanent magnets exist on the rotor. As the main materials in field winding machines are iron and  
20 copper, they are relatively inexpensive.

**[0009]** Conventionally, the field winding currents of synchronous field-winding machines enter the rotor through the use of slip rings. However, this approach is undesirable due to the need for a rotating mechanical contact that is subject to wear,  
25 the need for an auxiliary circuit to generate and regulate the field-winding current, and the extra space, mass, and cost associated with both the slip ring and auxiliary circuit. Rotary transformers or brushless exciters have also been used to transmit the electrical power consumed by the electromagnets. This, however, requires such a transformer as well as a power electronic circuit that transfers power to the rotor, thereby also  
30 negatively affecting cost, mass, and space.

**[0010]** This section provides background information related to the present disclosure which is not necessarily prior art.

## SUMMARY

**[0011]** This section provides a general summary of the disclosure, and is not a comprehensive disclosure of its full scope or all of its features.

5 **[0012]** A synchronous field-winding electric machine is presented. The electric machine includes a rotor and an AC stator arranged adjacent to and interoperable with the rotor. In one embodiment, the AC stator is configured with four or more phases to produce independent magnetic fields at two or more spatial harmonics. The rotor includes an excitation winding and a field winding. The field winding is electrically  
10 coupled to the excitation winding. The excitation winding and the field winding are configured to magnetically couple to the two or more spatial harmonics of the AC drive signal, such that the excitation winding is independently excitable from the field winding by different spatial harmonics of the AC drive signal. For example, the excitation winding is configured to magnetically couple to a given spatial harmonic of the two or  
15 more spatial harmonics of the AC drive signal while the field winding is configured to magnetically couple to another harmonic of the two or more spatial harmonics of the AC drive signal, such that the given harmonic differs from the another harmonic. A controller is electrically coupled to windings of the AC stator and independently controls the magnetic fields at the two or more spatial harmonics.

20 **[0013]** During operation, the torque of the electric machine is determined as a function of current in the field winding and current in the stator that produces the spatial harmonic which magnetically couples to the field winding.

25 **[0014]** In one embodiment, the AC stator is configured with five windings and the excitation winding is further defined as a three phase winding. The field winding may be electrically coupled by a rectifier circuit to the excitation winding, and the controller may be electrically coupled via an inverter circuit to the windings of the AC stator.

30 **[0015]** In some embodiments, the excitation winding is configured to magnetically couple to a given harmonic of the magnetic fields produced by the AC stator and the field winding is configured to magnetically couple to another harmonic which is three times the given harmonic.

**[0016]** In another aspect, the controller is configured to receive measurements of current in windings of the stator and convert the current measurements to d-q currents using a direct-quadrature-zero transformation. The controller in turn calculate an difference between the d-q currents and a set of reference currents, converts the  
5 differences to voltages and generate command voltages for the AC stator using an inverse direct-quadrature-zero transformation.

**[0017]** Further areas of applicability will become apparent from the description provided herein. The description and specific examples in this summary are intended  
10 for purposes of illustration only and are not intended to limit the scope of the present disclosure.

### DRAWINGS

**[0018]** The drawings described herein are for illustrative purposes only of selected embodiments and not all possible implementations, and are not intended to  
15 limit the scope of the present disclosure.

**[0019]** Figure 1 is a diagram of an electric machine interfaced with a controller;

**[0020]** Figure 2A is a cross-sectional view of an example embodiment of a stator  
20 coaxially arranged with a rotor;

**[0021]** Figure 2B is a schematic of an example stator circuit for use with the electric machine shown in Figure 2A;

**[0022]** Figure 2C is a schematic of an example rotor circuit for use with the  
25 electric machine shown in Figure 2A;

**[0023]** Figure 3A is an example of an alternative embodiment for the stator and rotor arrangement;  
30

**[0024]** Figure 3B is a schematic of an example rotor circuit for use with the electric machine shown in Figure 3A;

**[0025]** Figure 4 is a diagram of a feedback control technique used to control the electric machine; and

5 **[0026]** Figure 5 is a diagram depicting an example of a control algorithm implemented by the controller.

**[0027]** Corresponding reference numerals indicate corresponding parts throughout the several views of the drawings.

10 **DETAILED DESCRIPTION**

**[0028]** Example embodiments will now be described more fully with reference to the accompanying drawings.

**[0029]** Figure 1 depicts an electric machine 10 electrically coupled to a controller  
15 14. The electric machine 10 is comprised of a rotor and a stator. The stator is arranged adjacent to and interoperates with the rotor. In one embodiment, the stator is coaxially arranged with the rotor although other arrangements, including side-by-side, fall within the scope of this disclosure. An electric machine is a generic term for machines that utilize electromagnetic forces, including but not limited to electric motors  
20 and generators.

**[0030]** More specifically, the stator is designed with four or more phases which can produce independent magnetic fields at two or more spatial harmonics. The rotor includes an excitation winding and a field winding. The field winding is electrically coupled to the excitation winding, for example via a rectifier circuit. Other means for  
25 transferring the electric power from the excitation winding to the field winding are also contemplated by this disclosure. Different example embodiments for the stator and rotor will be further described below.

**[0031]** In this electric machine 10, the rotor windings are wound so that they  
30 couple with the different spatial harmonics produced by the stator windings. Using field-oriented control techniques, a magnetic field is generated by the stator windings at a given spatial harmonic associated with the excitation winding that is rotating with

respect to the excitation winding. This induces an AC voltage in the excitation winding of the rotor which is rectified into a DC voltage, and hence current, in the field winding of the rotor. The magnitude of the DC field current is therefore controlled by the magnitude of the rotating field. The AC stator will also produce a magnetic field component at the spatial harmonic associated with the field winding. This component will interact with the field-winding current, thereby producing torque. In other words, the excitation winding of the rotor is independently excitable from the field winding of the rotor by different spatial harmonics of the AC drive signal. With this approach, the power density of the synchronous field winding machine is significantly increased as compared to conventional field-winding designs.

**[0032]** The controller 14 regulates the current supplied to the windings of the stator in accordance with a control algorithm further described below. In an exemplary embodiment, the controller 14 is implemented as a microcontroller. It should be understood that the logic for the control algorithm can be implemented in hardware logic, software logic, or a combination of hardware and software logic. In this regard, controller 14 can be or can include any of a digital signal processor (DSP), microprocessor, microcontroller, or other programmable device which are programmed with software implementing the above described methods. It should be understood that alternatively the controller is or includes other logic devices, such as a Field Programmable Gate Array (FPGA), a complex programmable logic device (CPLD), or application specific integrated circuit (ASIC).

**[0033]** Figure 2A illustrates an example embodiment of a stator 21 coaxially arranged with a rotor 24. In this example, the stator has a 5-phase, 2-pole, single-layer distributed arrangement. More specifically, the stator 21 is configured with five phases: an a-phase winding, a b-phase winding, a c-phase winding, a d-phase winding and an e-phase winding installed on a stator core 22. Each winding is wound in two opposing slots formed in an inner circumferential surface of the stator core 22. For higher pole designs, other winding arrangements are contemplated by this disclosure. While a distributed arrangement is shown for the stator, a concentrated arrangement for the stator is suitable in other embodiments.

**[0034]** Referring to Figure 2B, the stator windings 25 are connected to each other, for example in a star configuration although other configurations are also contemplated by this disclosure. Voltage is applied to the stator windings 25 by an inverter circuit 23. In particular, the inverter circuit 23 is a five phase inverter circuit which employs five pairs of transistors, where each transistor pair is coupled between a voltage source. Control signals are applied to the gate terminals of the transistors by the controller 14 in accordance with a control algorithm, thereby generating the voltages applied to each winding of the stator 21. The inverter circuit 23 is intended to be illustrative and not limiting.

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**[0035]** With continued reference to Figures 2A and 2C, the rotor 24 includes an excitation winding 26 and a field winding 28. The excitation winding 26 is a 3-phase, 2-pole, single-layer distributed transformer windings, where the three-phases include an a-phase winding, a b-phase winding and a c-phase winding. Each winding is wound in two opposing slots formed on an outer circumferential surface of the rotor 24. The field winding 28 is a 1-phase, 6-pole, concentrated or distributed field winding. The field winding 28 is wound in slots interposed between each of the slots for the excitation windings. That is, the excitation winding has a 2-pole winding scheme and the field winding has a 6-pole winding scheme. Other possibilities include but are not limited to a 4-pole excitation winding and a 12-pole field winding; a 6-pole excitation winding and an 18-pole field winding, etc.

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20

**[0036]** A schematic for an example rotor circuit is shown in Figure 2C. In this example, the field winding 28 is electrically coupled by a rectifier circuit 27 to the excitation windings 26. In particular, the rectifier circuit 27 is a three-phase diode rectifier. That is, the rectifier circuit 27 is further defined by three pairs of diodes. For each phase, a first diode is electrically coupled between a given phase and the positive terminal of the field winding and a second diode is electrically coupled between the given phase and the negative terminal of the field winding. Other arrangements for a rectifier circuit or alternative coupling circuits also fall within the scope of this disclosure.

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**[0037]** Figure 3 illustrates another example embodiment for the stator 21 and the rotor 24. In this example, the stator employs a 5-phase, 2-pole design; whereas, the excitation winding of the rotor has a single-phase, six-pole design and the field winding

has a single-phase, two-pole design. In some embodiments, the rotor 24 may include permanent magnets in addition to the excitation winding and the field winding. Other arrangements for the stator 21 and rotor 24 also fall within the broader aspects of this disclosure.

5

**[0038]** With continued reference to the embodiment shown in Figure 2, the torque output of the electric machine 10 is given by:

$$\tau_{em} = \frac{5N_p}{4} M_{af} i_f i_{q3}, \quad (1)$$

where  $N_p$  is the number of poles,  $M_{af}$  is the mutual inductance between the field winding and armature windings of the stator, and  $i_f$  is the field current. As explained below,  $i_{d1}$  and  $i_{q1}$  can be used to induce voltages in the excitation winding, which are then rectified to generate the field current,  $i_{q3}$  is used to produce torque with the resulting field current, and  $i_{d3}$  can be used to achieve field weakening at high speeds (collectively referred to as d-q currents). Note that, in steady-state, these currents will be constant, which simplifies regulation.

15

**[0039]** To regulate the d-q currents and achieve a desired torque, a feedback control technique may be used as seen in Figure 4. Current in the stator windings is measured and serves as an input to the control algorithm. These current measurements are converted to d-q currents, for example using a direct-quadrature-zero transformation 42. The converted d-q currents are subtracted from the reference currents to produce an error signal which serves as an input to a feedback controller 43. D-q voltages are output by the feedback controller 43. The d-q voltages can then be converted to command voltages for the inverter circuit, for example using an inverse direct-quadrature-zero transformation 44. In this way, the command voltages are the voltages applied to each stator winding to achieve the target or desired d-q currents.

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**[0040]** Figure 5 illustrates the control algorithm in more detail. Again, the control algorithm applied to the five-phase electric machine shown in Figure 2. The fundamental spatial harmonic produced by the stator is used to excite the excitation winding of the rotor and the third spatial harmonic produced by the stator interacts with

30

the field current to produce torque. It is noted that the  $i_{d1}$  and  $i_{q1}$  currents also produce a small torque through their interaction with the excitation windings.

**[0041]** During operation, the current in the stator windings can be measured using a sense resistor or other known current sensing methods. In one example, this measured current is transformed into two sets of  $\alpha$ - $\beta$  currents, one set for each spatial harmonic, and a “zero sequence” current corresponding to the average of the phase currents. A Clarke transform may be used as follows:

$$\begin{bmatrix} i_{a1} \\ i_{\beta1} \\ i_{a3} \\ i_{\beta3} \\ i_0 \end{bmatrix} = \frac{2}{5} \begin{bmatrix} \cos\left(\frac{2\pi*0}{5}\right) & \cos\left(\frac{2\pi*1}{5}\right) & \cos\left(\frac{2\pi*2}{5}\right) & \cos\left(\frac{2\pi*3}{5}\right) & \cos\left(\frac{2\pi*4}{5}\right) \\ \sin\left(\frac{2\pi*0}{5}\right) & \sin\left(\frac{2\pi*1}{5}\right) & \sin\left(\frac{2\pi*2}{5}\right) & \sin\left(\frac{2\pi*3}{5}\right) & \sin\left(\frac{2\pi*4}{5}\right) \\ \cos\left(\frac{2\pi*0}{5}\right) & \cos\left(\frac{2\pi*3}{5}\right) & \cos\left(\frac{2\pi*6}{5}\right) & \cos\left(\frac{2\pi*9}{5}\right) & \cos\left(\frac{2\pi*12}{5}\right) \\ \sin\left(\frac{2\pi*0}{5}\right) & \sin\left(\frac{2\pi*3}{5}\right) & \sin\left(\frac{2\pi*6}{5}\right) & \sin\left(\frac{2\pi*9}{5}\right) & \sin\left(\frac{2\pi*12}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \end{bmatrix}$$

10 The zero sequence current  $i_\phi$  is preferably constrained to be zero due to the winding configuration.

The two sets of  $\alpha$ - $\beta$  currents are in turn transformed using a Park transformation into different synchronous reference frames with different electrical frequencies as follows:

15

$$\begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} = \begin{bmatrix} \cos(\theta_{s1}) & \sin(\theta_{s1}) \\ -\sin(\theta_{s1}) & \cos(\theta_{s1}) \end{bmatrix} \begin{bmatrix} i_{\alpha1} \\ i_{\beta1} \end{bmatrix},$$

$$\begin{bmatrix} i_{d3} \\ i_{q3} \end{bmatrix} = \begin{bmatrix} \cos(\theta_{s3}) & \sin(\theta_{s3}) \\ -\sin(\theta_{s3}) & \cos(\theta_{s3}) \end{bmatrix} \begin{bmatrix} i_{\alpha3} \\ i_{\beta3} \end{bmatrix}$$

$$\frac{d\theta_{s1}}{dt} = \omega_{s1},$$

$$\frac{d\theta_{s3}}{dt} = \omega_{s3}$$

In this example,  $\Theta_{s3}$  is the electrical rotor angle or the number of pole-pairs times the measured rotor angle and its derivative  $\omega_{s3}$  is the electrical rotor speed. The frequency  $\omega_{s1}$  is responsible for exciting the excitation winding, and can be chosen to keep the overall voltages and currents within the inverter limits.  $\Theta_{s3}$  is calculated from the measured rotor position. In one embodiment,  $\omega_{s1}$  is chosen to stay within voltage and

current limits and  $\Theta_{s1}$  is determined by integrating  $\omega_{s1}$ . The converted d-q currents are subtracted from the reference d-q currents to produce an error signal. The error signal is an input to a proportional-integral controller which outputs d-q voltages. The two sets of d-q voltages are converted into their  $\alpha$ - $\beta$  values using an inverse Park transformation as follows:

$$\begin{bmatrix} v_{\alpha 1} \\ v_{\beta 1} \end{bmatrix} = \begin{bmatrix} \cos(\theta_{s1}) & -\sin(\theta_{s1}) \\ \sin(\theta_{s1}) & \cos(\theta_{s1}) \end{bmatrix} \begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix},$$

$$\begin{bmatrix} v_{\alpha 3} \\ v_{\beta 3} \end{bmatrix} = \begin{bmatrix} \cos(\theta_{s3}) & -\sin(\theta_{s3}) \\ \sin(\theta_{s3}) & \cos(\theta_{s3}) \end{bmatrix} \begin{bmatrix} v_{d3} \\ v_{q3} \end{bmatrix}$$

The two-sets of  $\alpha$ - $\beta$  voltages are then used to determine duty cycles which generate the corresponding 5-phase voltages in an average-value sense. These 5-phase voltages are given by an inverse Clarke transform as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ \cos\left(\frac{2\pi*1}{5}\right) & \cos\left(\frac{2\pi*1}{5}\right) & \cos\left(\frac{2\pi*3}{5}\right) & \cos\left(\frac{2\pi*3}{5}\right) & 1 \\ \sin\left(\frac{2\pi*2}{5}\right) & \sin\left(\frac{2\pi*2}{5}\right) & \sin\left(\frac{2\pi*6}{5}\right) & \sin\left(\frac{2\pi*6}{5}\right) & 1 \\ \cos\left(\frac{2\pi*3}{5}\right) & \cos\left(\frac{2\pi*3}{5}\right) & \cos\left(\frac{2\pi*9}{5}\right) & \cos\left(\frac{2\pi*9}{5}\right) & 1 \\ \sin\left(\frac{2\pi*3}{5}\right) & \sin\left(\frac{2\pi*4}{5}\right) & \sin\left(\frac{2\pi*12}{5}\right) & \sin\left(\frac{2\pi*12}{5}\right) & 1 \end{bmatrix} \begin{bmatrix} v_{\alpha 1} \\ v_{\beta 1} \\ v_{\alpha 3} \\ v_{\beta 3} \\ v_0 \end{bmatrix},$$

where  $v_0$  is the zero-sequence voltage, which can be used as a degree of freedom to help stay within the voltage constraints of the inverter. To achieve the reference or desired d-q currents, the 5-phase voltages are applied to the corresponding stator windings. The controller 14 interfaces with the inverter circuit 23 to generate the voltages applied to the stator windings.

**[0042]** The control algorithm described above is merely illustrative and not intended to be limiting of control algorithms which may be used with the proposed electric machines. By swapping the fundamental and third harmonics, the control algorithm can be adapted for use with the electric machine shown in Figure 3. One skilled in the art could understand how to extend these control principles to other stator and rotor arrangements.

**[0043]** The foregoing description of the embodiments has been provided for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosure. Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. The same may also be varied in many ways. Such variations are not to be regarded as a departure from the disclosure, and all such modifications are intended to be included within the scope of the disclosure.

## CLAIMS

What is claimed is:

- 5 1. An electric machine, comprising:  
a rotor;  
an AC stator arranged adjacent to and interoperable with the rotor, wherein  
the AC stator is configured with four or more phases to independently produce  
magnetic fields at two or more spatial harmonics;  
wherein the rotor includes an excitation winding and a field winding and the  
10 field winding is electrically coupled to the excitation winding, wherein the excitation  
winding and the field winding are configured to magnetically couple to the two or  
more spatial harmonics of the AC drive signal, such that the excitation winding is  
independently excitable from the field winding by different spatial harmonics of the  
AC drive signal; and  
15 a controller electrically coupled to windings of the AC stator and  
independently controls the magnetic fields at the two or more spatial harmonics.
2. The electric machine of claim 1 wherein the torque of the electric machine  
is determined as a function of current in the field winding and current in the stator that  
20 produces the spatial harmonic which magnetically couples to the field winding.
3. The electric machine of claim 1 wherein the excitation winding is  
configured to magnetically couple to a given harmonic of the magnetic fields produced  
by the AC stator and the field winding is configured to magnetically couple to another  
25 harmonic which is three times the given harmonic.
4. The electric machine of claim 1 wherein the AC stator includes windings  
arranged to generate an AC drive signal.
- 30 5. The electric machine of claim 1 wherein the AC stator is configured with  
five windings and the excitation winding is further defined as a three phase winding.

6. The electric machine of claim 1 wherein the field winding is electrically coupled by a rectifier circuit to the excitation winding.

5 7. The electric machine of claim 1 wherein the controller is electrically coupled via an inverter circuit to the windings of the AC stator.

10 8. The electric machine of claim 1 wherein the controller is configured to receive measurements of current in windings of the stator and convert the current measurements to d-q currents using a direct-quadrature-zero transformation.

9. The electric machine of claim 8 where the controller calculate an difference between the d-q currents and a set of reference currents, converts the differences to voltages and generate command voltages for the AC stator using an inverse direct-quadrature-zero transformation.

15 10. An electric machine, comprising:  
a rotor;  
an AC stator arranged adjacent to and interoperable with the rotor, wherein the AC stator having windings arranged to independently produce magnetic fields at  
20 two or more spatial harmonics;

wherein the rotor includes an excitation winding and a field winding and the field winding is electrically coupled by a rectifier circuit to the excitation winding, such that the excitation winding is configured to magnetically couple to a given spatial harmonic of the two or more spatial harmonics of the AC drive signal and the  
25 field winding is configured to magnetically couple to another harmonic of the two or more spatial harmonics of the AC drive signal, where the given harmonic differs from the another harmonic; and

a controller electrically coupled via an inverter circuit to windings of the AC stator and independently controls the magnetic fields at the two or more spatial  
30 harmonics.

11. The electric machine of claim 10 wherein the torque of the electric machine is determined as a function of current in the field winding and current in the

stator that produces the spatial harmonic which magnetically couples to the field winding.

12. The electric machine of claim 10 wherein the excitation winding is  
5 configured to magnetically couple to a given harmonic of the magnetic fields produced by the AC stator and the field winding is configured to magnetically couple to another harmonic which is three times the given harmonic.

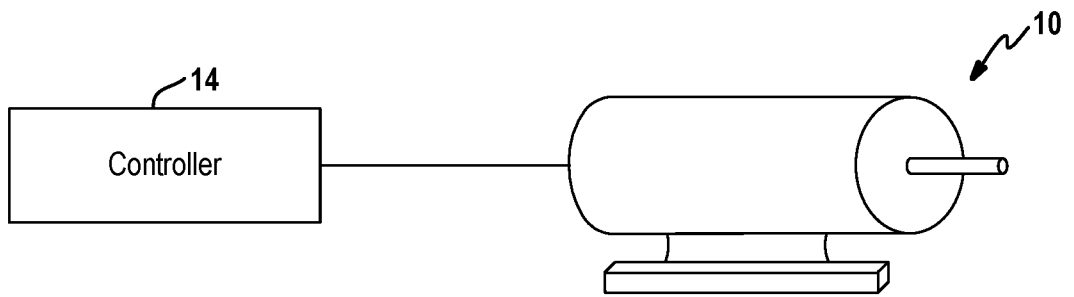
13. The electric machine of claim 10 wherein the excitation winding has a 2-  
10 pole winding arrangement and the field winding has a 6-pole winding arrangement.

14. The electric machine of claim 10 wherein the excitation winding has a 4-  
pole winding arrangement and the field winding has a 12-pole winding arrangement.

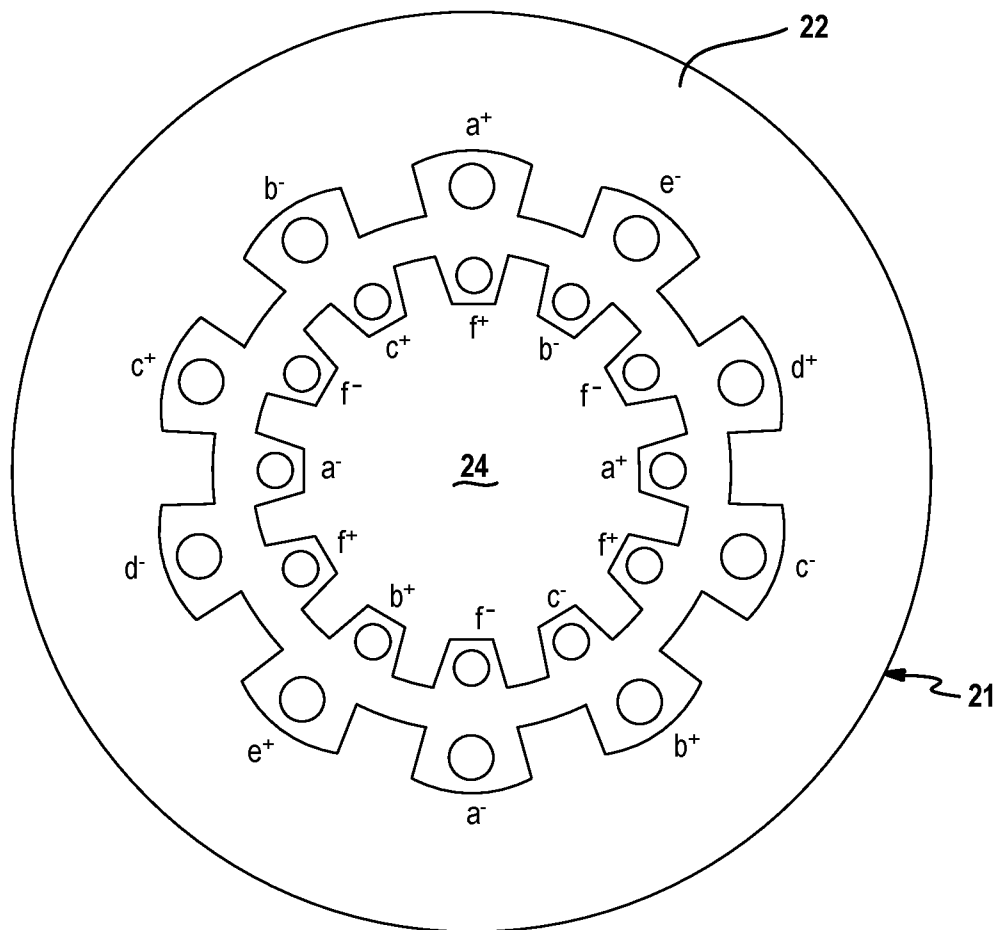
15. The electric machine of claim 10 wherein the AC stator has 4-pole  
15 winding arrangement.

16. The electric machine of claim 10 wherein the controller is configured to  
20 receive measurements of current in windings of the stator and convert the current measurements to d-q currents using a direct-quadrature-zero transformation.

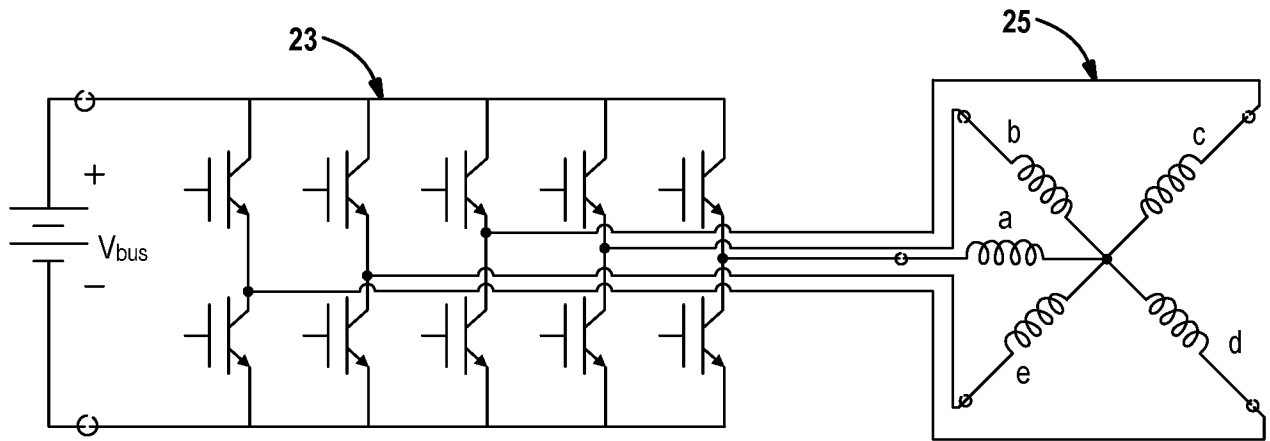
17. The electric machine of claim 16 where the controller calculate an  
25 difference between the d-q currents and a set of reference currents, converts the differences to voltages and generate command voltages for the AC stator using an inverse direct-quadrature-zero transformation.



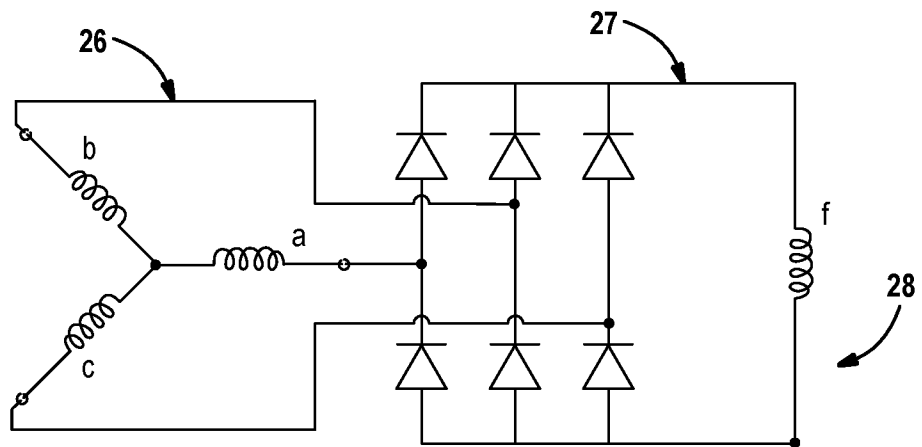
**FIG. 1**



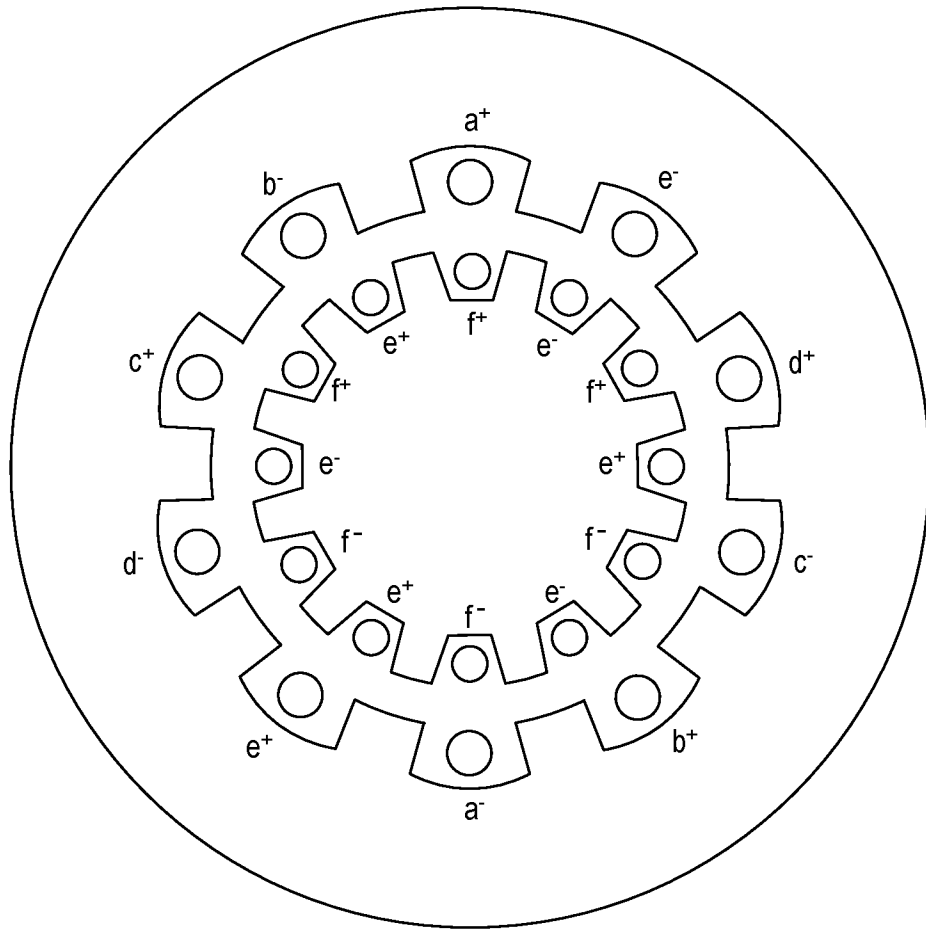
**FIG. 2A**



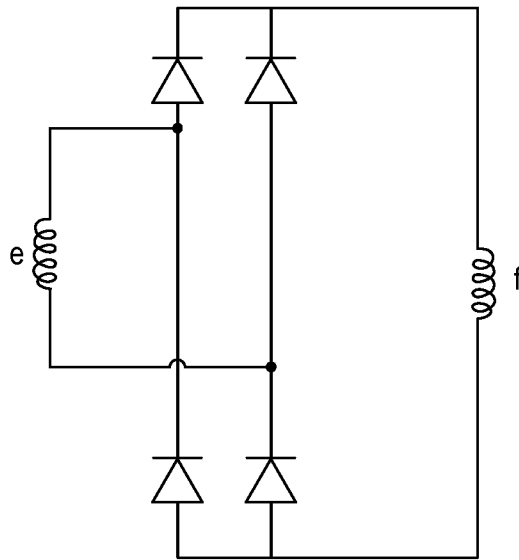
**FIG. 2B**



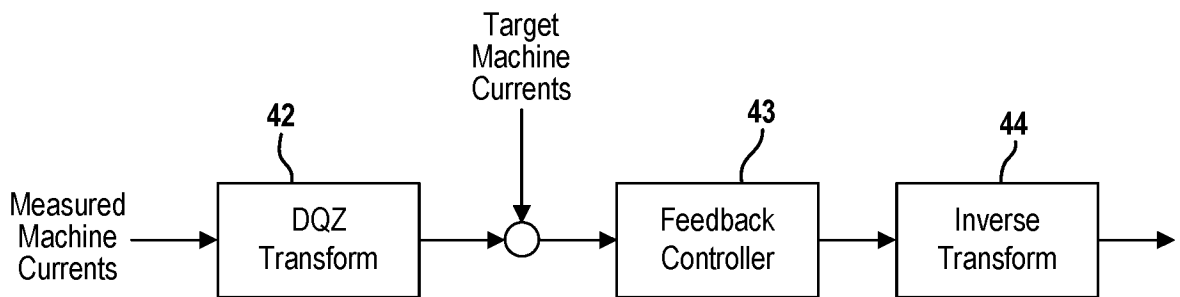
**FIG. 2C**



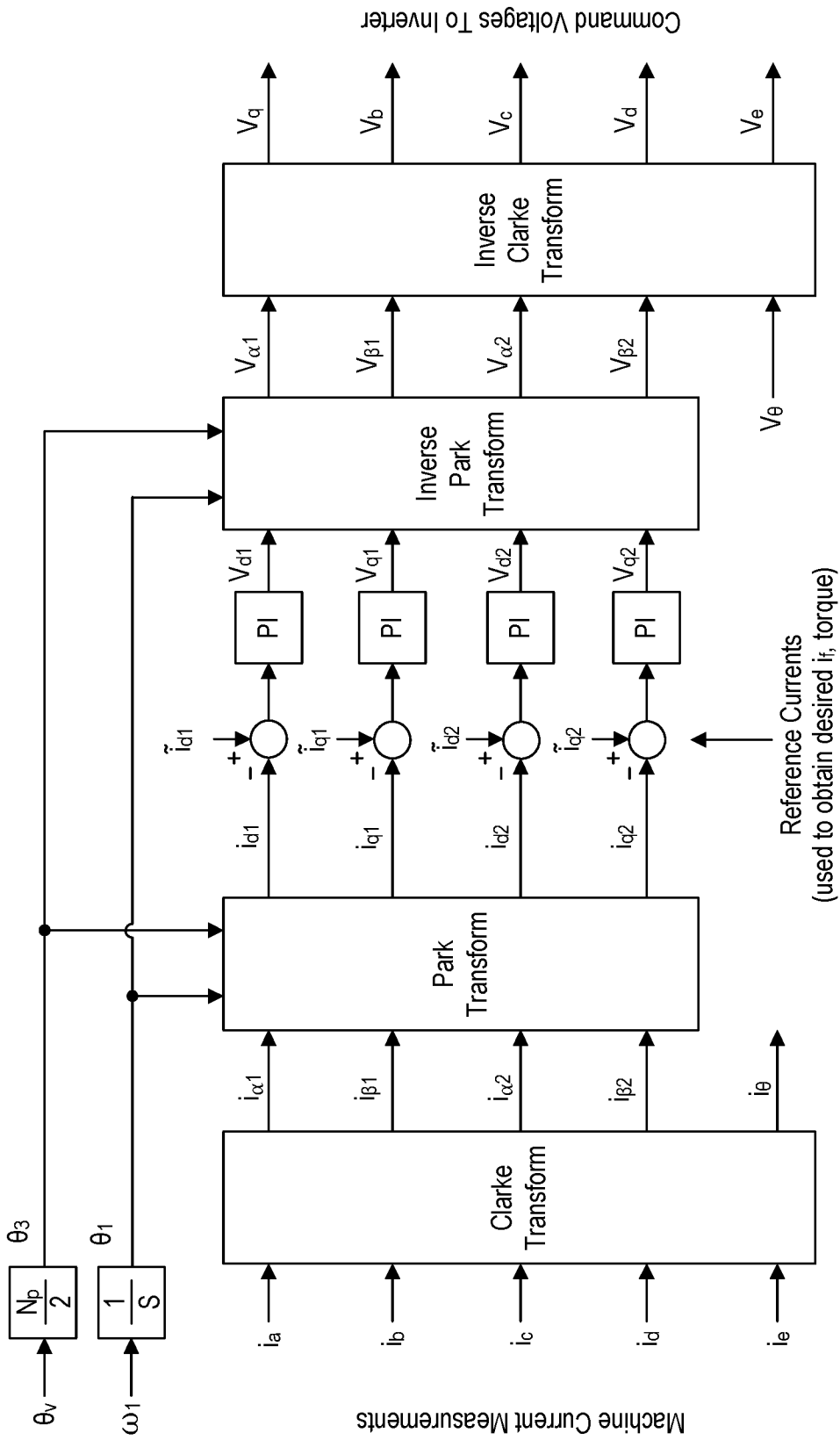
**FIG. 3A**



**FIG. 3B**



**FIG. 4**



Reference Currents  
(used to obtain desired  $i_t$ , torque)

**FIG. 5**

## PATENT COOPERATION TREATY

## PCT

## INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 2115-7802POA	<b>FOR FURTHER ACTION</b>	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. <b>PCT/US2019/027951</b>	International filing date ( <i>day/month/year</i> ) <b>17 April 2019 (17.04.2019)</b>	(Earliest) Priority Date ( <i>day/month/year</i> ) 17 April 2018 (17.04.2018)
Applicant <b>THE REGENTS OF THE UNIVERSITY OF MICHIGAN</b>		

This International search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

a. With regard to the **language**, the international search was carried out on the basis of:

the international application in the language in which it was filed

a translation of the international application into \_\_\_\_\_, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))

b.  This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6bis(a)).

c.  With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2.  **Certain claims were found unsearchable** (See Box No. II)

3.  **Unity of invention is lacking** (See Box No. III)

4. With regard to the **title**,

the text is approved as submitted by the applicant.

the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,

the text is approved as submitted by the applicant.

the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. With regard to the drawings,

a. the figure of the **drawings** to be published with the abstract is Figure No. 2A

as suggested by the applicant.

as selected by this Authority, because the applicant failed to suggest a figure.

as selected by this Authority, because this figure better characterizes the invention.

b.  none of the figures is to be published with the abstract.

**A. CLASSIFICATION OF SUBJECT MATTER****H02K 19/12(2006.01)i, H02P 21/14(2006.01)i, H02P 25/028(2016.01)i, H02P 25/03(2016.01)i**

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)

H02K 19/12; H02K 19/26; H02K 19/36; H02K 3/20; H02P 1/26; H02P 21/00; H02P 27/04; H02P 27/06; H02P 9/30; H02P 21/14; H02P 25/028; H02P 25/03

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) &amp; Keywords: rotor, stator, drive signal, phase, harmonic, excitation, field

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2014-007788 A (TOYOTA MOTOR CORP.) 16 January 2014 See paragraphs 19-36 and figures 1-5.	1-17
A	US 6051953 A (JOSEPH VITHAYATHIL) 18 April 2000 See column 3, lines 5-column 4, lines 21 and figures 1-2.	1-17
A	JP 2014-007837 A (TOYOTA MOTOR CORP.) 16 January 2014 See the entire document.	1-17
A	US 9813004 B2 (ABB TECHNOLOGY AG) 07 November 2017 See the entire document.	1-17
A	JP 2013-013246 A (TOYOTA MOTOR CORP. et al.) 17 January 2013 See the entire document.	1-17

 Further documents are listed in the continuation of Box C. See patent family annex.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

08 August 2019 (08.08.2019)

Date of mailing of the international search report

**09 August 2019 (09.08.2019)**

Name and mailing address of the ISA/KR

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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2019/027951**

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2014-007788 A	16/01/2014	None	
US 6051953 A	18/04/2000	None	
JP 2014-007837 A	16/01/2014	None	
US 9813004 B2	07/11/2017	CN 107889545 A EP 3245716 A1 EP 3245716 A4 US 10097123 B2 US 2016-0211787 A1 US 2018-0034396 A1 WO 2016-0115563 A1	06/04/2018 22/11/2017 20/02/2019 09/10/2018 21/07/2016 01/02/2018 21/07/2016
JP 2013-013246 A	17/01/2013	JP 5623346 B2	12/11/2014