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(71) Applicant: **SIEMENS GAMESA RENEWABLE ENERGY A/S** [DK/DK]; Borupvej 16, 7330 Brande (DK).

(72) Inventors: **AZAR, Ziad**; 41 Winchester Crescent, Sheffield, South Yorkshire S10 4ED (GB). **GROENDAHL, Erik**; Gl. Skolevej 2, 8653 Them (DK). **SAMANTA, Subhra**; Vesterhåb 60, 7430 Ikast (DK). **THOMAS, Arwyn**; 3 Almond Tree Road, Cheadle Hulme, Cheshire SK8 6HW (GB).

(74) Agent: **ASPACHER, Karl-Georg**; Postfach 22 16 34, 80506 München (DE).

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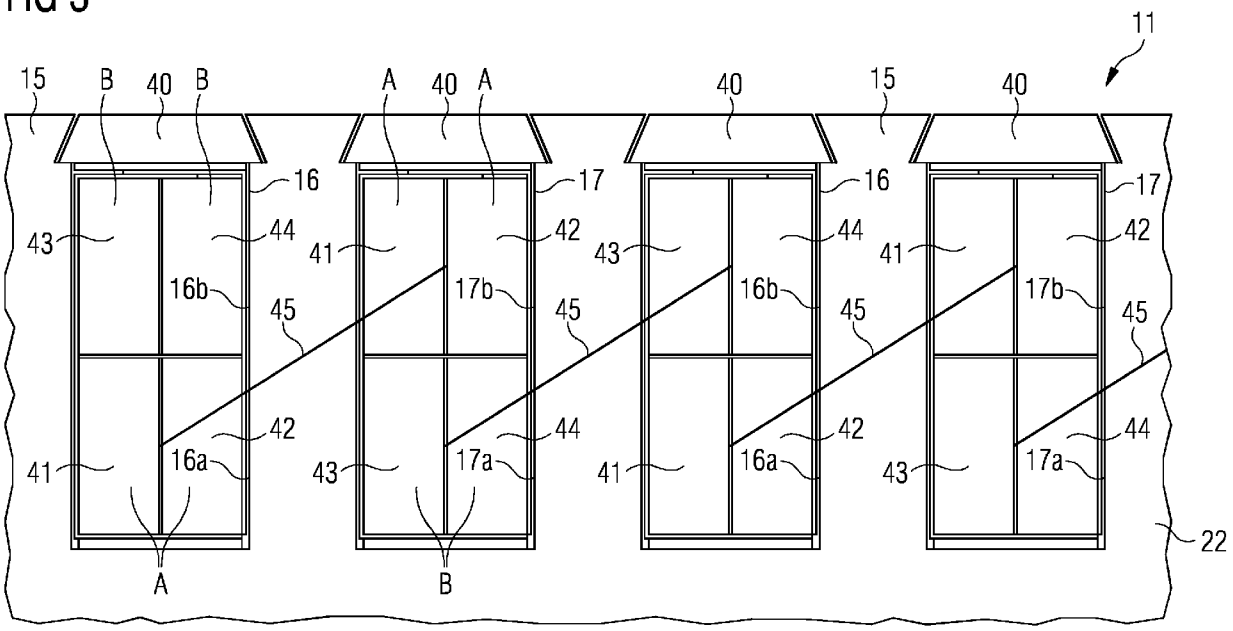
(54) Title: COIL FORMATION IN AN ELECTRIC MACHINE WITH CONCENTRATED WINDINGS

FIG 3



(57) Abstract: It is described an electric generator (10) comprising a stator (11) including: - a stator yoke (22), - a plurality of teeth (15), - a plurality of slots (16, 17) extending radially from the stator yoke (22) to respective radial slot ends (39), the plurality of slots (16) being circumferentially interposed between the teeth (15) of the stator (11), each slot (16, 17) including a bottom portion (16a, 17a) adjacent to the stator yoke (22) and a top portion (16b, 17b) adjacent to the respective radial slot end (39). The stator (11) further comprises a plurality of coils (41, 42, 43, 44) housed in the plurality of slots (16), each slot (16) housing at least one coil (41, 42, 43, 44) in the bottom portion (16a, 17a) and at least another coil (41, 42, 43, 44) in the top portion (16b, 17b), each coil (41, 42, 43, 44) housed in the bottom portion (16a, 17a) of a first slot (16, 17) of the plurality of slots being connected to another respective coil (41, 42, 43, 44) housed in the top portion (17b, 16b) of a second slot (17, 16) of the plurality of slots.

WO 2019/201595 A1

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DESCRIPTION

Coil formation in an electric machine with concentrated windings

Field of invention

The present invention relates to an electric machine with concentrated windings having a coil geometry permitting an increase of the fill factor, i.e. the ratio between the winding which is made of a good conducting material and the volume needed to house the winding.
The present invention may be particularly, but not exclusively, applied to the electric generator of a wind turbine.

Art Background

An electrical machine, such as an electric generator installed in a wind turbine, typically comprises a rotor which rotates relative to a stator.
The stator normally comprises a frame body longitudinally extending along a longitudinal axis and including a stator yoke and a plurality of teeth protruding according to a radial direction from the stator yoke to respective tooth radial ends. Each tooth extends also longitudinally between a first tooth longitudinal end and a second tooth longitudinal end. In the stator a plurality of slots are also defined, each slot being delimited circumferentially by two adjacent teeth and radially extending between the stator yoke and the respective tooth radial ends. Each slot houses a respective winding.
The present invention relates to concentrated windings, where each winding in each slot comprises a plurality of coils, each coil being connected with a respective coil of an adjacent slot through a respective end-winding, as shown in the attached figures 5 and 6.
Preformed coils are typically used, where the end winding must be designed to be long enough to allow the respective

coil to be deformed in order to allow the insertion in the respective slots.

With reference to the schematic sections of figures 5 and 6, each winding 17 in each slot 16 comprises two coils 19, respectively belonging to two phases of the electric generator and both extending along the entire radial depth of the respective slot 16. Each tooth 18 separates a pair of adjacent coils 19 housed in two respective adjacent slots 16, belonging to the same phase and connected by a respective end-winding 21.

In the solution of figure 5, the slots 16 are rectangular in shape and the teeth 18 are consequently tapered. In such design the double layer winding layout makes it difficult to insert coils with narrow coil width for side by side coil formation. In this case, it is necessary to have a longer coil overhang length of the end-windings to be able to make the coil insertion possible in the slot. Also, there is a possibility to damage the coil insulation during coil insertion process.

In the solution of figure 6, the teeth 18 are rectangular in shape and the slots 16 are consequently V-shaped. This design eases the coil insertion with shorter coil overhang length but it reduces performance of the machine as active material of tooth is replaced by non-active insulation material 16a in the middle of each slot, between the coils.

It is therefore desirable to provide a new concentrated winding design, in order to overcome or reduce the inconveniences above described.

Summary of the invention

Scope of the present invention is to provide an electric generator having a stator geometry permitting to avoid the above described inconveniences, by optimally reducing the coil overhang length, at the same time without compromising the performances of the electric generator.

This scope is met by the subject matter according to the independent claims. Advantageous embodiments of the present invention are described by the dependent claims.

According to a first aspect of the invention, it is provided an electric machine comprising a stator including:
- a stator yoke longitudinally extending along a longitudinal axis of the stator,
- a plurality of teeth protruding according to a radial direction orthogonal to the longitudinal axis) from the stator yoke to respective radial tooth ends,
- a plurality of slots extending radially from the stator yoke to respective radial slot ends, the plurality of slots being circumferentially interposed between the teeth of the stator, each slot including a bottom portion adjacent to the stator yoke and a top portion adjacent to the respective radial slot end,
- a plurality of coils housed in the plurality of slots, each slot housing at least one coil in the bottom portion and at least another coil in the top portion,
wherein each coil housed in the bottom portion of a first slot of the plurality of slots is connected to another respective coil housed in the top portion of a second slot of the plurality of slots.
The above described electric generator or motor may be advantageously integrated in a wind turbine.
According to a second aspect of the invention, it is provided a method of manufacturing an electric machine comprising the step of:
- providing a stator having a stator yoke longitudinally extending along a longitudinal axis of the stator, a plurality of teeth protruding according to a radial direction orthogonal to the longitudinal axis from the stator yoke to respective radial tooth ends and a plurality of slots extending radially from the stator yoke to respective radial slot ends, the plurality of slots being circumferentially interposed between the teeth of the stator, each slot including a bottom

portion adjacent to the stator yoke and a top portion adjacent to the respective radial slot end,
- providing a plurality of coils housed in the plurality of slots, each slot housing at least one coil in the bottom portion and at least another coil in the top portion,
- connecting each coil housed in the bottom portion of a first slot of the plurality of slots to another respective coil housed in the top portion of a second slot of the plurality of slots.

Advantageously, the stator geometry, and in particular the coil configuration, achieves the scope above defined. Further, the present invention allows easy insertion of coils in the slot without damaging insulation of the coil and increases the fill-factor of conducting material in the slot compared to the prior-art options. When manufacturing preformed concentrated winding stator coils for the electric machine of the present invention, the process of automated-taping may be with relative greater ease, in comparison to the above described prior art, due to the wider aperture of the coil after the coil winding phases.

According to an embodiment of the invention, the second slot of the plurality of slots is adjacent to the first slot, the first slot and the second slot being separated by one interposed tooth of the plurality of teeth.

According to another possible embodiment of the invention, each slot houses at least two coils in the bottom portion and two other coils in the top portion.

In particular, the coils may be connected such that the coil in the bottom portion which is more distanced from the interposed tooth is respectively connected to the coil in the top portion which is adjacent to the interposed tooth and that the coil in the bottom portion which is adjacent to the interposed tooth is respectively connected to the coil in the top portion which is more remote from the interposed tooth.

According to an embodiment of the invention, all the coils in the bottom portion belongs to a first electrical phase of the electric generator and all the coils in the top portion belongs to a second electrical phase of the electric generator. This avoids the need of insulation between coils of the same phase.

In embodiment with a segmented stator, i.e. wherein the stator comprises a plurality of segments, each segment may comprise two slots at the respective circumferential ends, each slot housing at least one coil in one of the bottom portion and the top portion the other of the bottom portion and the top portion being free of coils.
In such embodiment, a support may be provided at the respective circumferential ends of each stator segment, for filling any of the bottom portion or the top portion being free of coils during transportation.

It has to be noted that embodiments of the invention have been described with reference to different subject matters. In particular, some embodiments have been described with reference to apparatus type claims whereas other embodiments have been described with reference to method type claims. However, a person skilled in the art will gather from the above and the following description that, unless other notified, in addition to any combination of features belonging to one type of subject matter also any combination between features relating to different subject matters, in particular between features of the apparatus type claims and features of the method type claims is considered as to be disclosed with this document.

The aspects defined above and further aspects of the present invention are apparent from the examples of embodiment to be described hereinafter and are explained with reference to the examples of embodiment. The invention will be described in more detail hereinafter with reference to examples of embodiment but to which the invention is not limited.

Brief Description of the Drawing

Figure 1 shows a schematic section of a wind turbine including an electric generator with stator geometry according to the present invention

Figure 2 shows a cross section of a slot of a stator of an electric generator in accordance with the present invention.

Figure 3 shows a partial cross section of a stator of an electric generator in accordance with the present invention.

Figure 4 shows partial cross section of another embodiment of a stator of an electric generator in accordance with the present invention.

Figure 5 shows a partial cross section of a stator of an electric generator in accordance with the prior art.

Figure 6 shows a partial cross section of another stator of an electric generator in accordance with the prior art.

Detailed Description

The illustrations in the drawings are schematic. It is noted that in different figures, similar or identical elements are provided with the same reference signs.

Figure 1 shows a wind turbine 1 according to the invention. The wind turbine 1 comprises a tower 2, which is mounted on a non-depicted fundament. A nacelle 3 is arranged on top of the tower 2.
The wind turbine 1 further comprises a wind rotor 5 having two, three or more blades 4 (in the perspective of Figure 1

only two blades 4 are visible). The wind rotor 5 is rotatable around a rotational axis Y. When not differently specified, the terms axial, radial and circumferential in the following are made with reference to the rotational axis Y.

The blades 4 extend radially with respect to the rotational axis Y.

The wind turbine 1 comprises a concentrated winding electric generator 10.

The wind rotor 5 is rotationally coupled with the electric generator 10 by means of a rotatable main shaft 9.

According to other possible embodiments of the present invention (not represented in the attached figures), the wind rotor 5 is rotationally coupled directly with the electric generator 10 (direct-drive generator configuration).

A schematically depicted bearing assembly 8 is provided in order to hold in place the rotor 5. The rotatable main shaft 9 extends along the rotational axis Y. The permanent magnet electric generator 10 includes a stator 11 and a rotor 12.

The rotor 12 is radially external to the stator 11 and is rotatable with respect to the stator 11 about the rotational axis Y. According to other embodiments of the present invention (not shown) the rotor is radially internal to the stator 11.

According to other possible embodiments of the present invention (not represented in the attached figures), the present invention can be applied to any electrical generator or motor which has concentrated winding topology, for example geared drive-trains or electrical machine of the synchronous or asynchronous types.

Figure 2 shows a partial schematic view of a cross section, orthogonal to the rotational axis Y, of one embodiment of the stator 11.

The stator includes a stator yoke 22 (only partially represented in the attached figures) longitudinally extending along the longitudinal axis of the stator, from which a plurality of teeth 15 (only two teeth 15 are partially repre-

sented in the attached figure 2) protrude according to a radial direction up to respective radial tooth ends 38.
The stator includes also a plurality of slots 16, 17 (one slot 16 is shown in figure 2) extending radially from the stator yoke 22 to respective radial slot ends 39.
The plurality of slots 16, 17 are circumferentially interposed between the teeth 15 of the stator 11.
Each slot 16, 17 houses a respective concentrated winding and a wedge 40. The wedges 40 are provided at radial slot ends 39 for protecting and keeping in place the respective windings.
The concentrated windings comprise a plurality of coils 41, 42, 43, 44, as better detailed in the following.
At each slot end 39 a respective wedge 40 is provided for radially closing the respective slot 16, 17. Each wedge 40 circumferentially extends in the respective slot 16, 17 between two notches 35 respectively provided at the radial tooth ends 38 of the two teeth 15 which circumferentially delimit the respective slot 16, 17.
The slot 16 includes a bottom portion 16a adjacent to the stator yoke 22 and a top portion 16b adjacent to the respective radial slot end 39.
The slot 16 includes two coils 41, 42 in the bottom portion 16a, both belonging to a first phase A of the electric generator 11, and two coils 43, 44 in the top portion 16b, both belonging to a second phase B of the electric generator 11.
With reference to **Figure 3**, two pair of adjacent slots 16, 17 are shown. Each pair of slots 16, 17 include a first slot 16 (as in figure 2) and a second slot 17, separated from the first slot 16 by an interposed tooth 15 of the plurality of teeth 15.
Similarly to the first slot 16, the second slot 17 includes also a bottom portion 17a adjacent to the stator yoke 22 and a top portion 17b adjacent to the respective radial slot end 39.
Differently from the first slot 16, the second slot 17 includes the two coils 41, 42 of the first phase in the top portion 17b and the two coils 43, 44 of the second phase B in the bottom portion 17a.

Each coil 41, 42 housed in the bottom portion 16a of the first slot 16 is connected to another respective coil 41, 42 housed in the top portion 17b of the second slot 17 by means of a respective end-windings 45.

Conversely, each coil 43, 44 housed in the bottom portion 17a of the second slot 17 is connected to another respective coil 43, 44 housed in the top portion 16b of the first slot 16 by means of a respective end-windings 45.

The representation of end-windings 45 in the cross section of figure 3 is schematic. In reality the end-windings 45 has a curved shape protruding axially in air from the slots 16, 17.

As shown in the embodiment of **Figure 3**, the coils 41, 42, 43, 44 are connected such that the coil 41, 43 in the bottom portion 16a, 17a which is more distanced from the tooth 15 interposed between the slots 16, 17 is respectively connected to the coil 41, 43 in the top portion 17b, 16b which is adjacent to the interposed tooth 15 and that the coil 42, 44 in the bottom portion 16a, 17a which is adjacent to the interposed tooth 15 is respectively connected to the coil 42, 44 in the top portion 17b, 16b which is more remote from the interposed tooth 15.

Such form of connection limits the overhang of the end-windings 45.

Figure 4 shows a partial schematic view of a cross section, orthogonal to the rotational axis Y, of another embodiment of the stator 11, where the stator 11 is segmented and comprises a plurality of segments 51. Each segment 51 comprises one first end slot 26 at one circumferential end 52 and a second end slot 27 at the other circumferential end 53.

Each end slot 26, 27 has a circumferential extension corresponding to half the circumferential extension of each of the plurality of slots 16, 17 of the stator 11, in such a way that, when two segments 51 are circumferentially joined together, a slot 16, 17 of the stator 11 is formed.

To such purpose, the coils 41, 42, 43, 44 are already formed and inserted in the end slot 26, 27, in such a way that, when two segments 51 are circumferentially joined together a slot

16, 17 of the stator 11 is formed with the respective coils 41, 42, 43, 44 already included therein.

Each of the end slots 26, 27 comprises respective bottom portions 26a, 27a adjacent to the stator yoke 22 and top portions 26b, 27b adjacent to the respective radial slot end 39. Respective half wedges 40a, 40b are provided at each end slot 26, 27, in such a way that, when two segments 51 are circumferentially joined together, a wedge 40 of the stator 11 is formed.

In general, in a segmented stator 11, each end slot 26, 27 houses at least one coil 41, 42, 43, 44 in one of the bottom portion 26a, 27a and the top portion 26b, 27b the other of the bottom portion 26a, 27a and the top portion 26b, 27b being free of coils.

In the embodiment of **Figure 4** shows when the two segments 51 are circumferentially joined together a first slot 16 (as in figure 2) is formed. Therefore in one bottom portion 27a of the end slot 27, both coils 41, 42 of the first phase A are provided while the respective top portion 27b is left free of coils and in the one top portion 26b of the other end slot 26, both coils 43, 44 of the second phase B are provided while the respective bottom portion 26a is left free of coils.

The manufacturing of the two segments 51 and there subsequent assembly in an electrical machine, e.g. the electric generator 10, results in a balanced magnetic inductance in all of the plurality of coils (41, 42, 43, 44).

When manufacturing the stator 11, a support 61 at each circumferential end 52, 53 of the segment 51 of the stator 11 for filling any of the bottom portion 26a, 27a or the top portion 26b, 27b being free of coils. This is useful during storing and transportation of the segment 51.

CLAIMS

1. Electric machine (10) comprising a stator (11) including:
- a stator yoke (22) longitudinally extending along a longitudinal axis (Y) of the stator (11),
- a plurality of teeth (15) protruding according to a radial direction orthogonal to the longitudinal axis (Y) from the stator yoke (22) to respective radial tooth ends (38),
- a plurality of slots (16, 17) extending radially from the stator yoke (22) to respective radial slot ends (39), the plurality of slots (16, 17) being circumferentially interposed between the teeth (15) of the stator (11), each slot (16, 17) including a bottom portion (16a, 17a) adjacent to the stator yoke (22) and a top portion (16b, 17b) adjacent to the respective radial slot end (39),
- a plurality of coils (41, 42, 43, 44) housed in the plurality of slots (16), each slot (16) housing at least one coil (41, 42, 43, 44) in the bottom portion (16a, 17a) and at least another coil (41, 42, 43, 44) in the top portion (16b, 17b),
wherein each coil (41, 42, 43, 44) housed in the bottom portion (16a, 17a) of a first slot (16, 17) of the plurality of slots is connected to another respective coil (41, 42, 43, 44) housed in the top portion (17b, 16b) of a second slot (17, 16) of the plurality of slots.

2. Electric machine (10) as claimed in claim 1, wherein the second slot (17, 16) of the plurality of slots is adjacent to the first slot (16), the first slot (16, 17) and the second slot (17, 16) being separated by one interposed tooth (15) of the plurality of teeth (15).

3. Electric machine (10) as claimed in claim 1 or 2, wherein each slot (16) houses at least two coils (41, 42; 43, 44) in the bottom portion (16a, 17a) and two other coils (43, 44; 41, 41) in the top portion (16b, 17b).

4. Electric machine (10) as claimed in claims 2 and 3, wherein the coils (41, 42, 43, 44) are connected such that the coil (41, 43) in the bottom portion (16a, 17a) which is more distanced from the interposed tooth (15) is respectively connected to the coil (41, 43) in the top portion (17b, 16b) which is adjacent to the interposed tooth (15) and that the coil (42, 44) in the bottom portion (16a, 17a) which is adjacent to the interposed tooth (15) is respectively connected to the coil (42, 44) in the top portion (17b, 16b) which is more remote from the interposed tooth (15).

5. Electric machine (10) as claimed in claim 3 or 4, wherein all the coils (41, 42; 43, 44) in the bottom portion (16a, 17a) belongs to a first electrical phase (A) of the electric generator (10) and all the coils (43, 44; 41, 41) in the top portion (16b, 17b) belongs to a second electrical phase (B) of the electric generator (10).

6. Electric machine (10) as claimed in any of the above claims, wherein the stator (11) comprises a plurality of segments (51), each segment (51) comprising two end slots (26, 27) at the respective circumferential ends (52, 53), each end slot (26, 27) having a circumferential extension corresponding to half the circumferential extension of each of the plurality of slots (16, 17) of the stator (11), each end slot (26, 27) housing at least one coil (41, 42, 43, 44) in one of the bottom portion (26a, 27a) and the top portion (26b, 27b) the other of the bottom portion (26a, 27a) and the top portion (26b, 27b) being free of coils.

7. Method of manufacturing an electric machine (10) comprising the step of:
- providing a stator (11) having a stator yoke (22) longitudinally extending along a longitudinal axis (Y) of the stator (11), a plurality of teeth (15) protruding according to a radial direction orthogonal to the longitudinal axis (Y) from the stator yoke (22) to respective radial tooth ends (38) and a plurality of slots (16, 17) extending radially from the

stator yoke (22) to respective radial slot ends (39), the plurality of slots (16) being circumferentially interposed between the teeth (15) of the stator (11), each slot (16, 17) including a bottom portion (16a, 17a) adjacent to the stator yoke (22) and a top portion (16b, 17b) adjacent to the respective radial slot end (39),
- providing a plurality of coils (41, 42, 43, 44) housed in the plurality of slots (16), each slot (16) housing at least one coil (41, 42, 43, 44) in the bottom portion (16a, 17a) and at least another coil (41, 42, 43, 44) in the top portion (16b, 17b),
- connecting each coil (41, 42, 43, 44) housed in the bottom portion (16a, 17a) of a first slot (16, 17) of the plurality of slots to another respective coil (41, 42, 43, 44) housed in the top portion (17b, 16b) of a second slot (17, 16) of the plurality of slots.

8. Method of manufacturing as claimed in claim 7, wherein the stator (11) is manufactured as a plurality of segments (51), each segment (51) comprising two end slots (26, 27) at the respective circumferential ends (52, 53), each end slot (26, 27) having a circumferential extension corresponding to ha circumferential extension of each of the plurality of slots (16, 17) of the stator (11), the method comprising the step of providing in each slot (16, 17) at least one coil (41, 42, 43, 44) in one of the bottom portion (26a, 27a) and the top portion (26b, 27b) the other of the bottom portion (26a, 27a) and the top portion (26b, 27b) being free of coils.

9. Method of manufacturing as claimed in claim 8, wherein the method includes the step of forming a slot (16, 17) of the plurality of slots (16, 17) of the stator (11), the slot (16, 17) housing a plurality of coils (41, 42, 43, 44), by circumferentially joining two segments (51),

10. Method of manufacturing as claimed in claim 8, the method comprises the step of providing at least a support (61) at

a respective circumferential end (52, 53) of one of the segments of the stator (11) for filling any of the bottom portion (26a, 27a) or the top portion (26b, 27b) being free of coils during transportation.

FIG 1

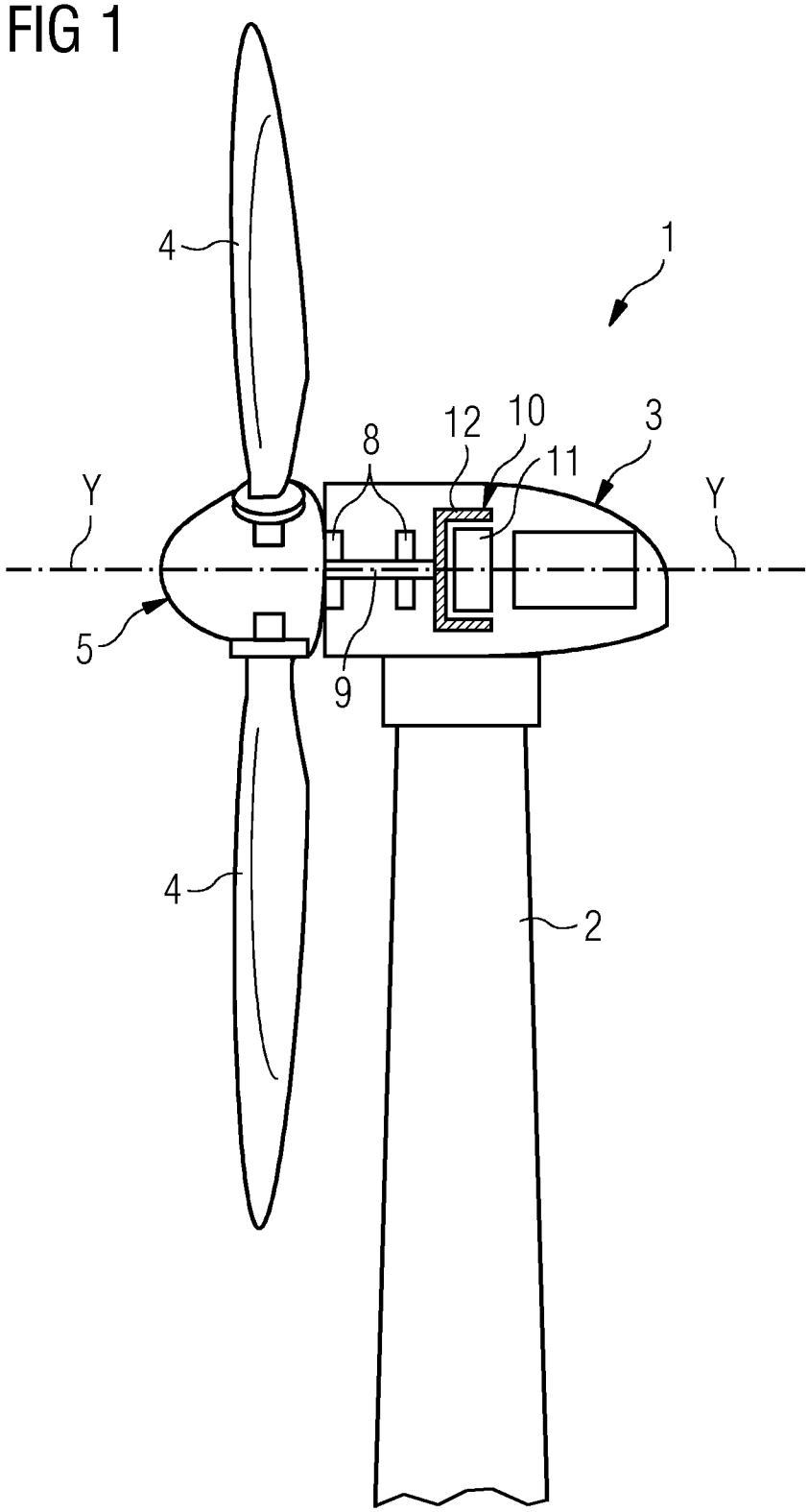
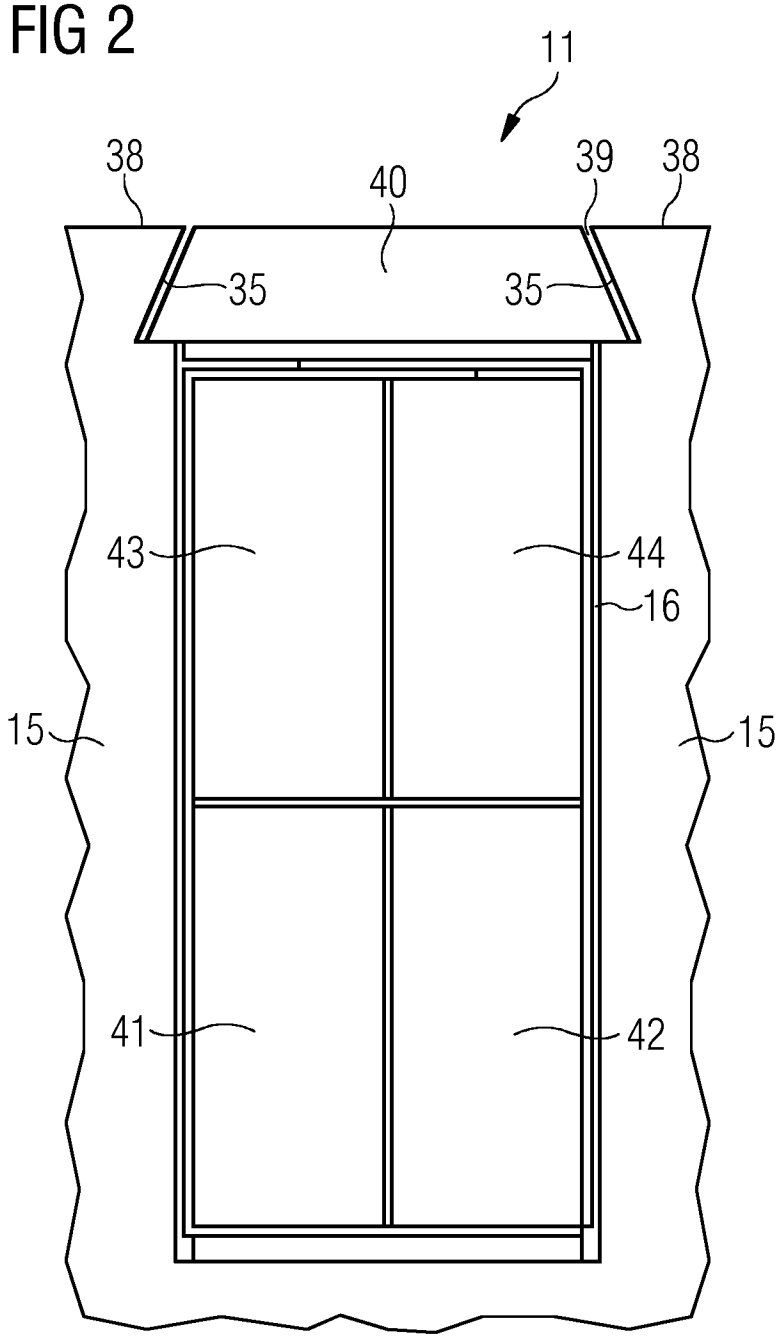


FIG 2



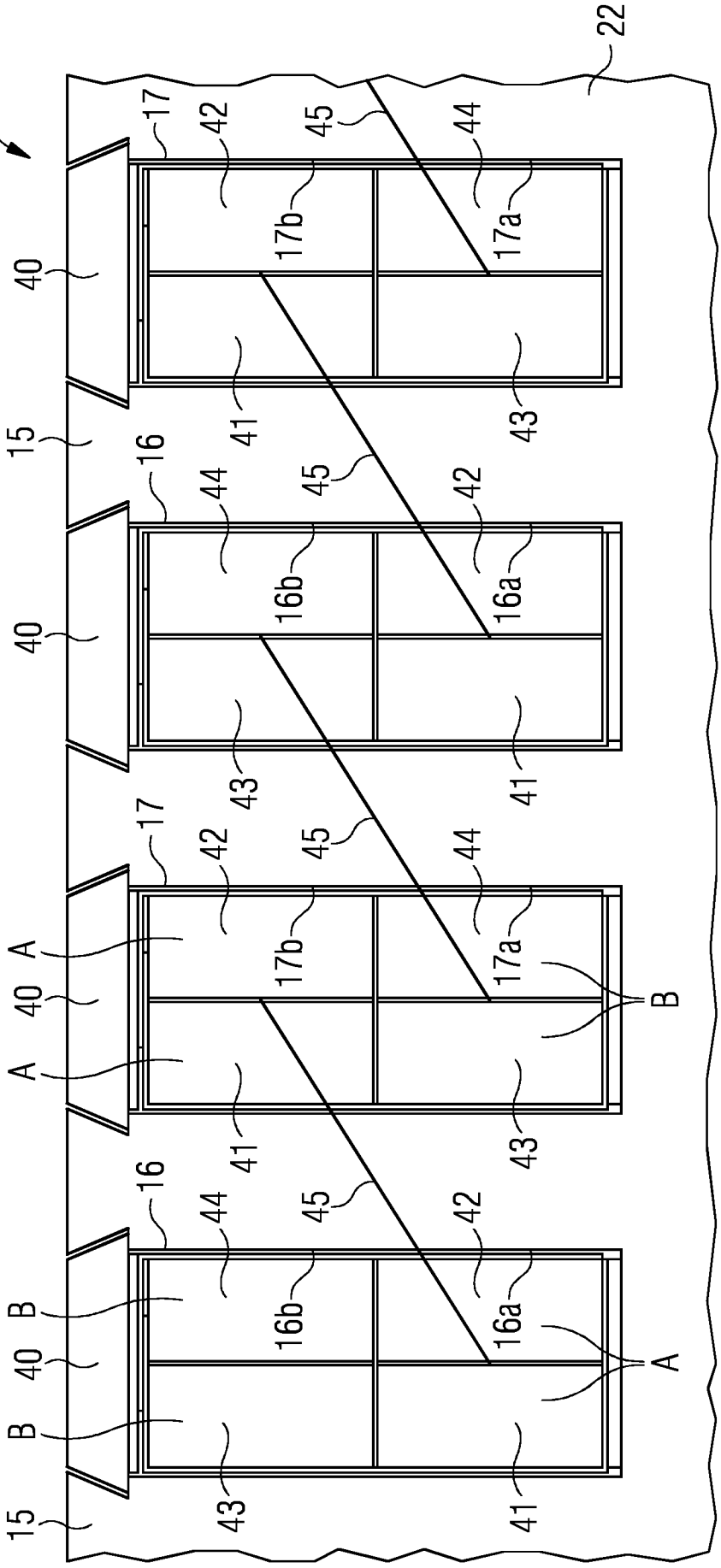


FIG 3

FIG 4

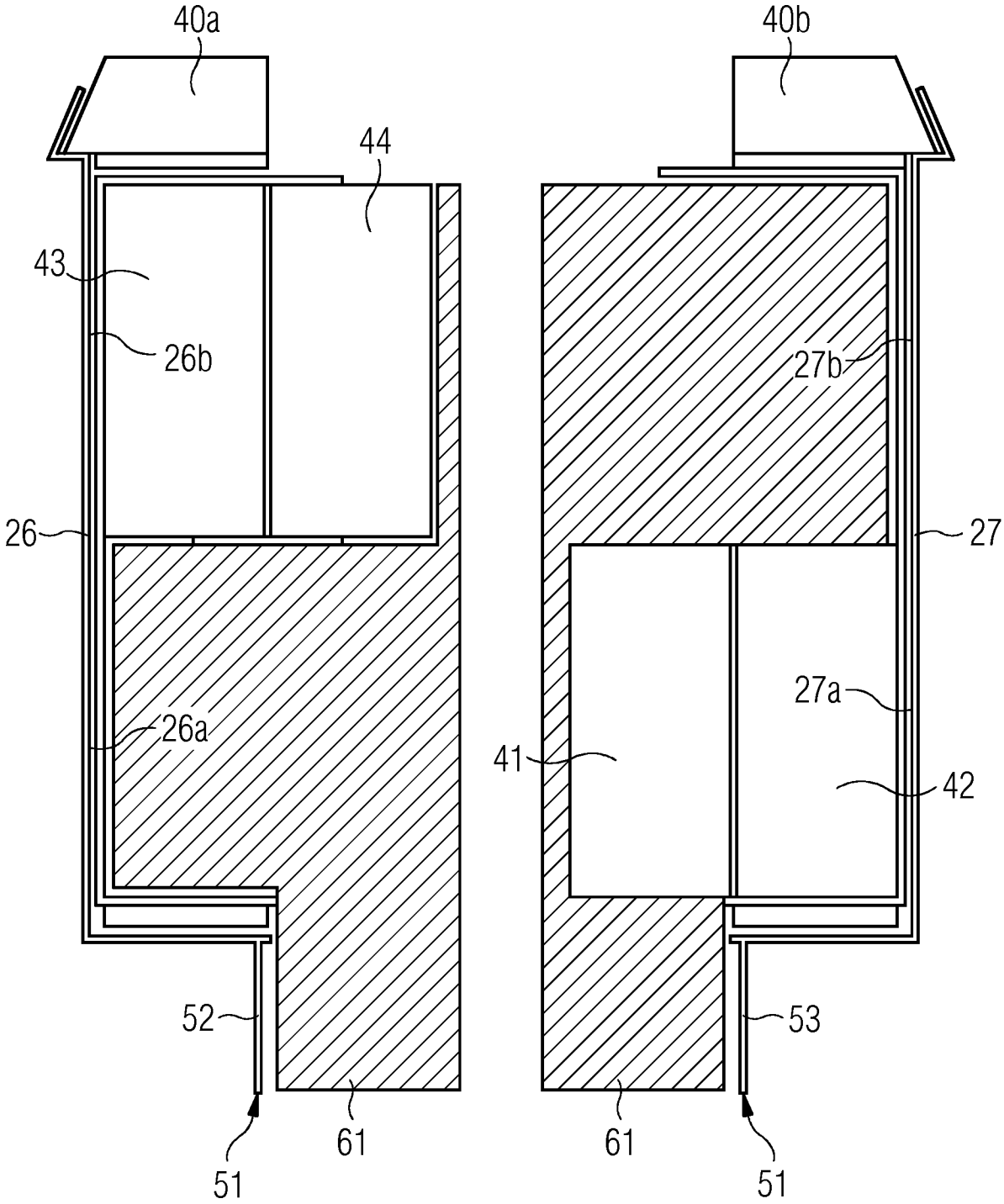


FIG 5 PRIOR ART

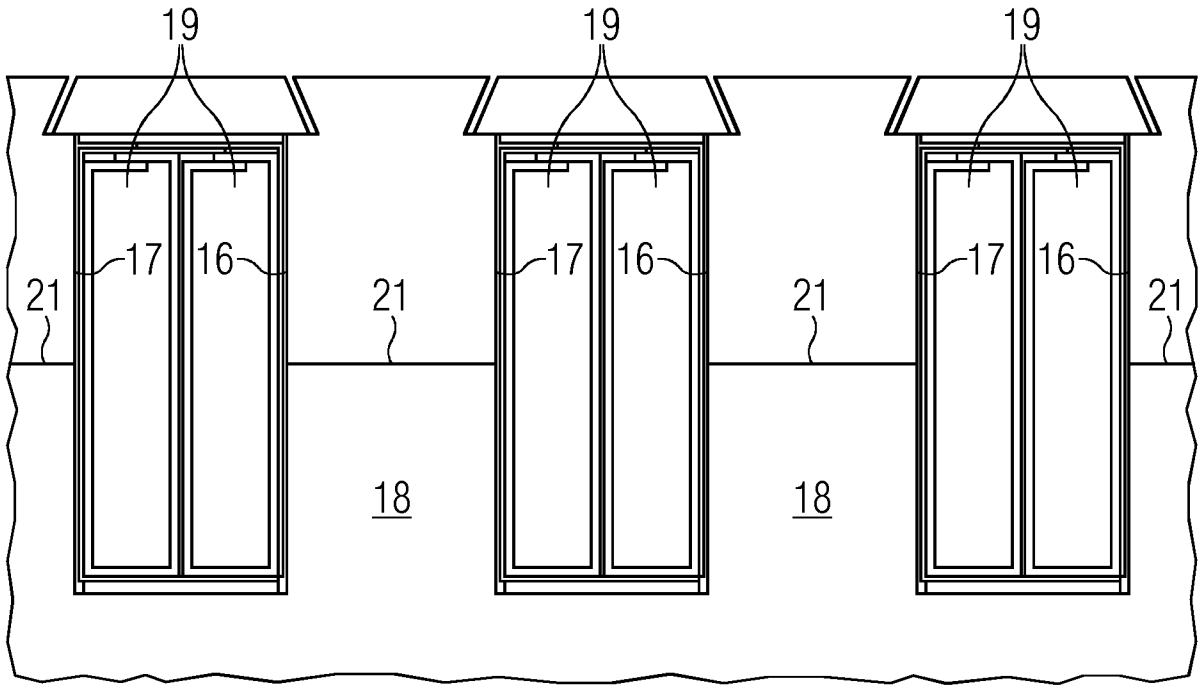
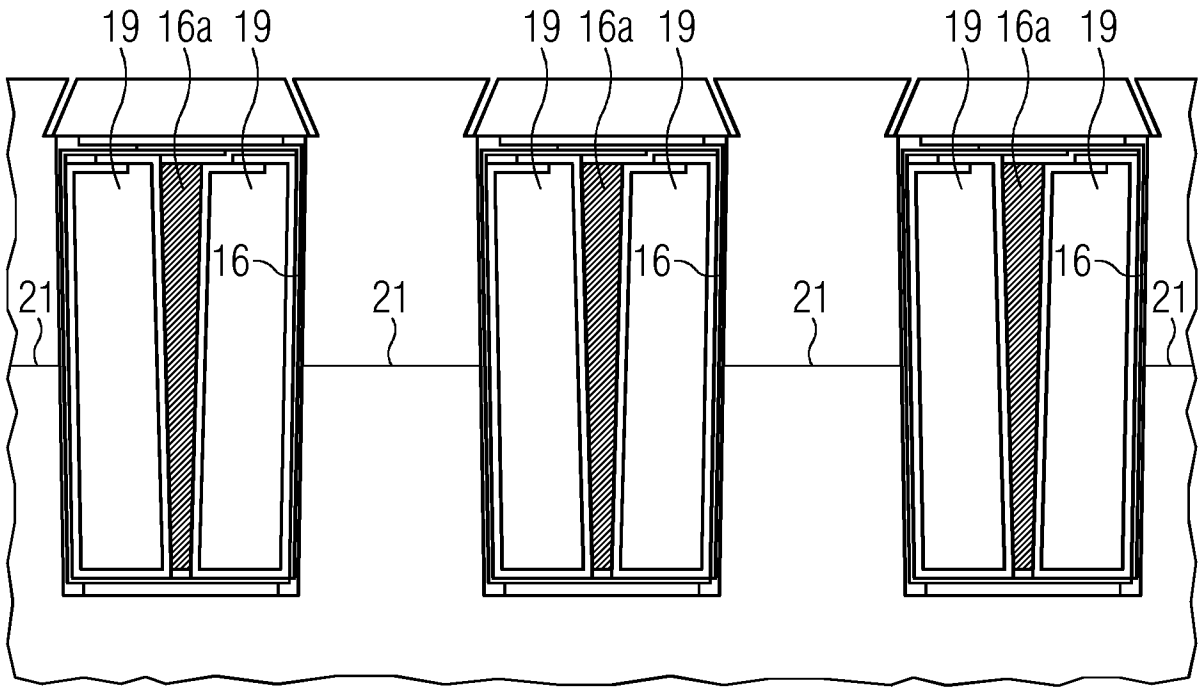


FIG 6 PRIOR ART



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/058345

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K3/12 H02K3/28 H02K3/48 H02K1/27 H02K3/487
H02K7/18
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)
H02K

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	EP 2 498 381 A1 (SIEMENS AG [DE]) 12 September 2012 (2012-09-12) abstract; figures 2-4 paragraph [0059] -----	1,2,7 3-6,8-10
Y	US 2012/001512 A1 (DAJAKU GURAKUQ [DE]) 5 January 2012 (2012-01-05) abstract; figure 5a -----	3-5
Y	US 2015/084454 A1 (NOER BJARNE [DK]) 26 March 2015 (2015-03-26) abstract; figure 1 paragraphs [0004] - [0006] -----	6,8-10
A	US 2005/258703 A1 (KOUDA SHINJI [JP] ET AL) 24 November 2005 (2005-11-24) abstract; figure 6 -----	3-5

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Date of the actual completion of the international search	Date of mailing of the international search report
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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	Güvener, Cem

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

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