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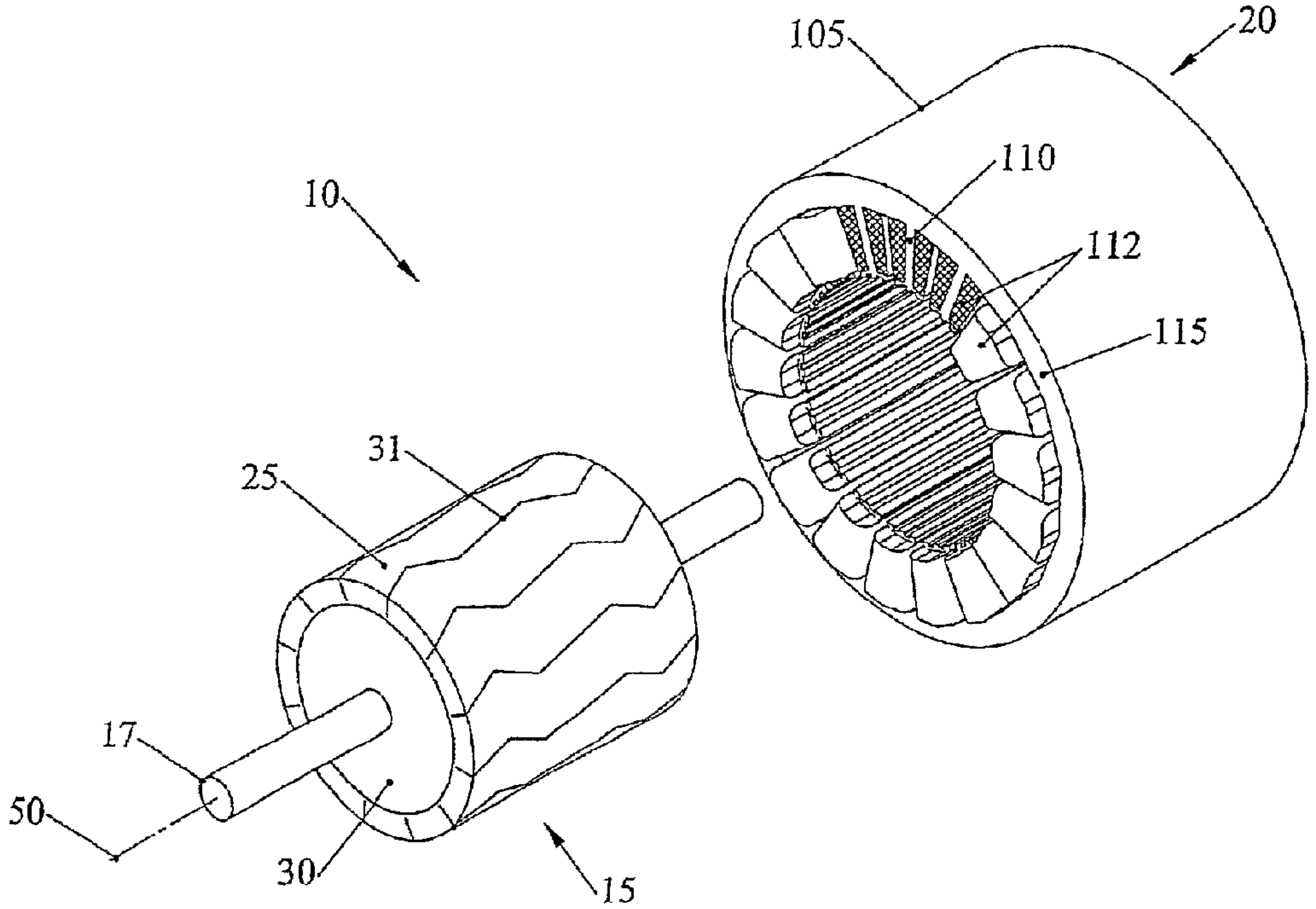
(54) **Title:** ELECTRICAL MACHINE AND METHOD OF CONTROLLING THE SAME



(57) **Abrégé/Abstract:**

A method of controlling an electrical machine having a stator and a rotor. The stator includes a core and a plurality of windings disposed on the core in a three-phase arrangement. The three-phase arrangement includes a first, second, and third phases having a first, second, and third terminals, respectively. The rotor is disposed adjacent to the stator to interact with the stator. The method includes applying a pulsed voltage differential to the first and second terminals resulting in movement of the rotor; monitoring the back electromotive force (BEMF) of the third phase to sense rotor movement; after the applying and monitoring steps, monitoring the BEMF of each of the first, second, and third phases to determine whether the rotor is rotating in a desired direction, and electrically commutating the motor when the rotor is rotating in the desired direction and zero or more other conditions exist.

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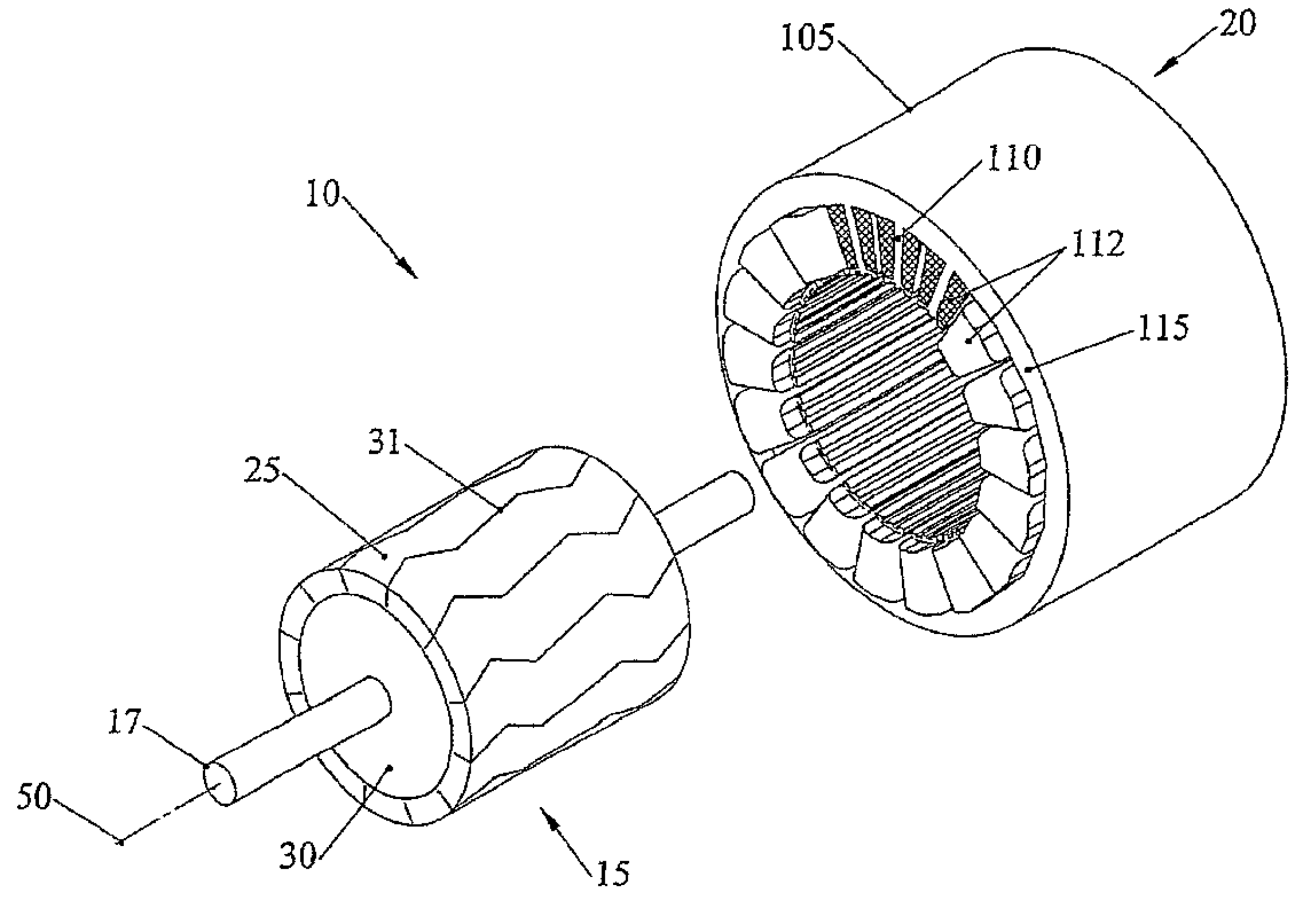


(57) **Abstract:** A method of controlling an electrical machine having a stator and a rotor. The stator includes a core and a plurality of windings disposed on the core in a three-phase arrangement. The three-phase arrangement includes a first, second, and third phases having a first, second, and third terminals, respectively. The rotor is disposed adjacent to the stator to interact with the stator. The method includes applying a pulsed voltage differential to the first and second terminals resulting in movement of the rotor; monitoring the back electromotive force (BEMF) of the third phase to sense rotor movement; after the applying and monitoring steps, monitoring the BEMF of each of the first, second, and third phases to determine whether the rotor is rotating in a desired direction, and electrically commutating the motor when the rotor is rotating in the desired direction and zero or more other conditions exist.

ELECTRICAL MACHINE AND METHOD OF CONTROLLING THE SAME

[0001]

FIELD OF THE INVENTION

[0002] The invention relates to an electrical machine and specifically a brushless electrical machine.

BACKGROUND AND SUMMARY OF THE INVENTION

[0003] Brushless direct current (BLDC) motors are becoming more prevalent in industries that typically did not use BLDC motors. For example, the need for increased efficiency in the heating and air conditioning market has led to the use of BLDC motors for powering the blower. BLDC motors, which may also be referred to as electrically commutated motors (ECM), include a rotor having a plurality of magnetic poles (e.g., a plurality of poles produced with permanent magnets) of alternating polarity disposed on a surface of a rotor core, and a stator that receives electrical power and produces a magnetic field in response thereto. The magnetic field of the stator interacts with a magnetic field of the rotor to cause movement of the rotor.

[0004] BLDC motors require a means for determining the position of the rotor in order to commutate the motor. One method of commutating the motor is referred to as "sensorless" motor commutation. Sensorless motor commutation is often performed by sensing the back electromotive force (BEMF) produced by the motor. Typically, the BEMF signal produced in the stator windings is not large enough for sensorless motor commutation until the speed of the rotor reaches about ten percent of the rated motor speed. As a result, a means of starting the motor without using the BEMF signal may be necessary.

[0005] For a three-phase motor, one method of starting the motor is to align the rotor by providing current to one phase of the motor and wait until the rotor has stopped oscillating, then step through the other phases of the motor (with each subsequent phase getting shorter, thus ramping the speed up without any position feedback) until the rotor reaches 10% of rated speed. This method has at least two drawbacks. First, the time required during the align phase can be long where the inertia of the attached load is large and the friction is low (e.g., if the load is a large blower). Second, information about the load (e.g., inertia and torque) is typically required in order to step the motor.

[0006] The purpose of aligning the rotor as described earlier is to start the motor from a known rotor position. One way to avoid this aligning process is by knowing the rotor position some other method. The second drawback described earlier can be overcome by not stepping blindly (without rotor position information) but by knowing the rotor position at almost zero speed.

[0007] In one embodiment, the invention provides a method of controlling an electrical machine having a stator and a rotor. The stator includes a core and a plurality of windings disposed on the core in a three-phase arrangement. The three-phase arrangement includes a first phase, a second phase, and a third phase having a first terminal, a second terminal, and a third terminal, respectively. The rotor is disposed adjacent to the stator to interact with the stator. The method includes the steps of applying a pulsed voltage differential to the first and second terminals resulting in movement of the rotor; monitoring the back electromotive force (BEMF) of the third phase to sense rotor movement; after the applying and monitoring steps, monitoring the BEMF of each of the first, second, and third phases to determine the direction of rotation of the rotor; determining whether the rotor is rotating in a desired direction, and electrically commutating the motor when the rotor is rotating in the desired direction and zero or more other conditions exist.

[0007a] In another embodiment, the invention provides a method of controlling an electrical machine comprising a stator comprising a core and a plurality of windings disposed on the core in a three-phase arrangement, the three-phase arrangement comprising a first phase, a second phase, and a third phase having a first terminal, a second terminal, and a third terminal, respectively, and a rotor disposed adjacent to the stator to interact with the stator, the method comprising: applying a first pulsed voltage differential to the terminals resulting in a current from the second terminal to the first and third terminals, the first pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a first value having a relation to a current resulting from the first pulsed voltage differential, applying a second pulsed voltage differential to the terminals resulting in a current from the first terminal to the second and third terminals, the second pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a second value having a relation to a current resulting from the second pulsed voltage differential, applying a third pulsed voltage differential to the terminals resulting in a current from the third terminal to the first and second terminals, the third pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a third value having a relation to a current resulting from the third pulsed voltage differential, determining which of the first, second, and third values having a relation to the current has the largest magnitude, applying a fourth pulsed voltage differential to the terminals based on the determining step, the fourth pulsed voltage differential resulting in movement of the rotor; after the applying the fourth pulsed voltage differential step, monitoring the BEMF of each of the first, second, and third phases to determine the direction of rotation of the rotor, determining whether the rotor is rotating in a desired direction, and electrically commutating the motor when the rotor is rotating in the desired direction.

[0007b] In a further embodiment, the invention provides a method of controlling an electrical machine comprising a stator comprising a core and a plurality of windings disposed on the core in a three-phase arrangement, the three-phase arrangement comprising a first phase, a second phase, and a third phase having a first terminal, a second terminal, and a third terminal, respectively, and a rotor disposed adjacent to the stator to interact with the stator, the method comprising: applying a first pulsed voltage differential from the second terminal to the first terminal, the first pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a first value having a relation to a current resulting from the first pulsed voltage differential, applying a second pulsed voltage differential from the first terminal to the third terminal, the second pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a second value having a relation to a current resulting from the second pulsed voltage differential, applying a third pulsed voltage differential from the third terminal to the second terminal, the third pulsed voltage differential resulting in substantially no movement of the rotor, acquiring a third value having a relation to a current resulting from the third pulsed voltage differential, determining which of the first, second, and third values having a relation to the current has the largest magnitude; applying a fourth pulsed voltage differential to the terminals based on the determining step, the fourth pulsed voltage differential resulting in movement of the rotor; after applying the fourth pulsed voltage and monitoring the BEMF, monitoring the BEMF of each of the first, second, and third phases; monitoring for changes in at least one of the following conditions whether the BEMF of the first phase is greater than the BEMF of the second phase, whether the BEMF of the second phase is greater than the BEMF of the third phase, and whether the BEMF of the third phase is greater than the BEMF of the first phase; determining the direction of rotation of the rotor based on the monitoring for changes step; determining whether the rotor is rotating in a desired direction; and electrically commutating the motor when the rotor is rotating in the desired direction.

[0007c] In yet another embodiment, the invention provides a method of controlling an electrical machine including a stator having a core and a plurality of windings disposed on the core in a multiple phase arrangement, and a rotor disposed adjacent to the stator to interact with the stator, the method comprising: applying a first pulsed voltage to a first terminal of a first phase of the multiphase arrangement; monitoring back electromotive force (BEMF) of at least one phase of the multiphase arrangement; obtaining a first monitored value of BEMF; obtaining a second monitored value of BEMF at an interval after the obtaining the first monitored value; comparing the second monitored value of BEMF against the first monitored value of BEMF; determining whether the rotor is rotating based of the comparison; and preventing movement of the rotor in response to the second monitoring value of BEMF being substantially similar to or greater than the first monitored value of BEMF.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Fig. 1 is partial exploded view of the stator and rotor of a brushless permanent magnet electrical machine.

[0009] Fig. 2 is an isometric view showing the geometry used to define an arc of magnetization skew (β) on the rotor.

[0010] Fig. 3 is a longitudinal view of one construction of the rotor of Fig. 1.

[0011] Fig. 4 is a cross-sectional view of a stator core and a rotor capable of being used in the electrical machine of Fig. 1.

[0012] Fig. 5 is a block diagram of an electrical drive circuit capable of powering the electric machine of Fig. 1.

[0013] Fig. 6 is an example of a stator-winding pattern in a double-layer arrangement with compact coils for an 18-slot, 12-pole, 3-phase machine.

[0014] Fig. 7 is an example of a stator-winding pattern in a single-layer arrangement with compact coils for an 18-slot, 12-pole, 3-phase machine.

[0015] Fig. 8 has schematic diagrams representing three pulses being applied to a three-phase motor.

[0016] Fig. 9 represents a comparison of the BEMFs for a three phase machine.

DETAILED DESCRIPTION

[0017] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms "connected," "coupled," "supported," and "mounted" and variations thereof herein are used broadly and, unless otherwise stated, encompass both direct and indirect connections, couplings, supports, and mountings. In addition, the terms connected and coupled and variations thereof herein are not restricted to physical and mechanical connections or couplings.

[0018] Portions of an exemplary brushless direct current (BLDC) machine incorporating the invention is shown in Figs. 1-6. However, the invention is not limited to the machine disclosed in Figs. 1-6; other BLDC machines can incorporate the invention.

[0019] Fig. 1 is a partial exploded view of the stator and rotor of one construction of an electrical machine (e.g., motor, generator, etc.). For Fig. 1, the electrical machine is a motor 10 having a rotor 15 and a stator 20. The rotor 15 is coupled to a shaft 17. In general, the stator 20 receives electrical power, and produces a magnetic field in response thereto. The magnetic field of the stator 20 interacts with a magnetic field of the rotor 15 to produce mechanical power on the shaft 17. The invention below refers to the electrical motor 10.

[0020] The rotor 15 includes a plurality of magnetic poles 25 of alternating polarity exhibited on a surface of a rotor core 30. The rotor core 30 includes laminations (e.g., magnetic steel laminations), and/or solid material (e.g., a solid magnetic steel core), and/or compressed powdered material (e.g., compressed powder of magnetic steel). One construction of the rotor 15 includes a sheet of permanent magnet (e.g., hard magnetic) material disposed on the rotor core 30. Another construction of the rotor 15 can include a plurality of strips of permanent magnet material attached (e.g., with adhesive) around the core 30. The permanent magnet material can be magnetized by a magnetizer to provide a plurality of alternating magnetic poles. Additionally, the number of magnetic strips can be different than the number of rotor magnetic poles. Yet another construction of the rotor 15 contains blocks of permanent magnet material placed inside the rotor core 30.

[0021] The description of the invention is not limited to a particular mechanical construction, geometry, or position of the rotor 15. For example, Fig. 1 shows the rotor 15 located inside and separated by a radial air gap from the stator 20. In another construction, the rotor 15 can be positioned radially exterior to the stator 20 (i.e., the machine is an external- or outer- rotor machine.)

[0022] One method to reduce cogging and ripple torque, which may be necessary in some BLDC motors, is skewing the magnetization of the magnetic poles 25 with respect to the stator 20. Alternatively, stator teeth of the stator 20 can be skewed with respect to the rotor magnetization. As shown in Figs. 1 and 2, the “magnetization” of the rotor 15 refers to the line pattern 31 along the length of the rotor 15 delineating alternating magnetic poles 25 on the rotor core 30.

[0023] Fig. 2 illustrates the geometrical concepts involved in defining the magnetization skew of the rotor. The arc of magnetization skew can be defined as the arc (β), measured in radians in between the longitudinal lines 32 and 33 (see Fig. 2) on the rotor surface facing the air-gap, which separates the stator and the rotor.

[0024] Fig. 3 is a schematic diagram of one construction of the rotor 15 divided into a plurality of axial sections 55 (e.g., 70, 71, and 72) along the rotational axis 50 of the rotor 15. The number of axial sections 55 can vary and is not limiting on the invention. An axial section 55 refers to a portion of the rotor 15 differentiated by imaginary lines 60. Imaginary lines 60 refer to locations on the rotor 15 where the direction of skew of the magnetization pattern 31 changes. One construction of the rotor 15 includes alternating magnetic poles with substantially the same arc of magnetization skew (β) along each axial section 55, resulting in a herringbone pattern of magnetization. The length of each axial section 55 can vary.

[0025] Fig. 3 shows one construction of the rotor 15 including three axial sections 70, 71, and 72. The stator 20 interacts with one or more of the three axial sections 70, 71, and 72. The first axial section 70 includes magnetic poles aligned with a first skew direction, the second axial section 71 includes magnetic poles aligned with a second skew direction, and the third axial section 72 includes magnetic poles aligned with the first skew direction. The total number of axial sections and the total number of ratings for a given motor profile are not limiting on the invention.

[0026] Various designs of stator 20 can be used to interact with each construction of the rotor 15 described above and shown in Figs. 1-3. The following is a description of one construction of the invention that includes the rotor 15 disposed radially from the stator 20. With reference to Figs. 1 and 4, the stator 20 includes a stator core 105 having a plurality of stator teeth 110 and stator windings 112. In one construction, the stator core 105 includes a stack of magnetic steel laminations or sheets. In other constructions, the stator core 105 is formed from a solid block of magnetic material, such as compacted powder of magnetic steel. The stator windings 112 include electrical conductors placed in the slots

120 and around the plurality of teeth 110. Other constructions and types of the stator core 105 and stator windings 112 known to those skilled in the art can be used and are not limiting on the invention.

[0027] Electrical current flowing through the stator windings 112 produces a magnetic field that interacts with the magnetization of the rotor 15 to provide torque to the rotor 15 and shaft 17. The electrical current can be an (m) phase alternating current (AC), where (m) is an integer greater than or equal to two. The electrical current can have various types of waveforms (e.g., square wave, quasi-sine wave, etc). The stator windings 112 receive electrical current from an electrical drive circuit. One construction of an electrical drive circuit 125 configured to power the motor 10 is shown in Fig. 5. In general, the drive circuit 125 receives power from a power source 130 and drives the motor 10 in response to an input (e.g., from an input device 130 such as a user input).

[0028] With reference to Fig. 5, the drive 125 receives AC power from a power source 130. The AC power is provided to a filter 140 and a rectifier 145 that filter and rectify the AC power, resulting in a bus voltage VDC. The bus voltage VDC is provided to an inverter 150 and to a voltage divider 155. The voltage divider reduces the bus voltage 155 to a value capable of being acquired by the controller 160 (at terminal 162). The controller 160 includes a processor 165 and a memory 170. Generally speaking, the processor reads, interprets, and executes instructions stored in the memory 170 to control the driver 125. Of course, the controller 160, which may be in the form of a microcontroller, can include other components such as a power supply, an analog-to-digital converter, filters, etc. The controller 160 issues drive signals at terminals 175 and 180 to control the inverter 150. The inverter includes power electronic switches (e.g., MOSFETs, IGBTs) to vary the flow of current to the motor. For example, and in one construction, the inverter can be in the form of a bridge circuit. A sense resistor 185 is used to generate a voltage having a relation to the bus current of the inverter 150. The voltage of the sensor resistor 185 is provided to the controller 160 at terminal 187. Other methods of sensing current can be used to sense the bus current. It is also envisioned that the controller 160 can receive values associated with the phase currents provided by the inverter 150. The drive circuit 125 also includes a BEMF voltage divider 190 and variable gain amplifiers 195. The BEMF voltage divider 190 and variable gain amplifiers 195A-C provide voltage values to the controller 160 at terminals 200A-C. The voltage values provided to the controller 160 by the variable gain amplifiers 195A-C have a relation to the BEMF of each phase voltage.

[0029] In operation, the controller 160 controls the motor by providing drive signals to the inverter based on inputs received at the controller 160. Example inputs include an input received from input device 135, the bus voltage, the bus current, and the BEMF voltages. Further discussion regarding the operation of the machine is provided below.

[0030] Fig. 4 shows a cross-sectional profile of a motor cross-section perpendicular to axis 50 used in one motor construction (the stator windings 112 are not shown in Fig. 6). The stator core 105 includes the plurality of stator teeth 110, slots 120, and a back iron portion 115. Each of the plurality of stator slots 120 receives one or more stator coils, the assembly of which constitutes the stator windings 112. The stator windings receive a multi-phase electrical current, where the number of phases (m) is an integer greater than or equal to two. The number (t) of stator teeth 110 equals the number of slots 120, where (t) is an integer. A slot 120 is defined by the space between adjacent stator teeth 110. The rotor 15 is produced, in one construction, by fixing three arc shaped magnets 26 on a rotor core 30. Other rotor designs and constructions are also possible. A magnetizer is used to produce on the rotor 15 a number (p) of alternating magnetic poles that interact with the stator 20.

[0031] The stator core 105 having the above-described construction can be used to design and manufacture motors with various (m) electric phases, with windings 112 composed of compact coils (see the winding patterns in Fig. 6 and Fig. 7) and rotors having poles (p). One construction of the stator windings 112 includes a double layer arrangement of compact coils (Fig. 6), which are placed around each tooth (i.e. the coils have a pitch of 1-slot). In this double layer arrangement, each slot is shared by two coil sides, each of the coil sides belonging to a different coil and phase. The two coil sides sharing a slot can be placed side by side or one on top of the other. The double-layer winding pattern for an example 18-slot, 12-pole, 3-phase winding is shown in Fig. 6. Another construction of the windings 112 includes a single layer arrangement of compact coils (Fig. 7), which are placed around every other tooth (i.e. the coils have a pitch of 1-slot and are only placed around half the number of teeth). In this single layer arrangement, each slot contains only one coil side. The single layer winding pattern for an example 18-slot, 12-pole, 3-phase winding is shown in Fig. 7. A typical manufacturing technique to provide a double layer stator winding with compact coils includes use of a needle or gun winder. A typical manufacturing technique to provide a single layer stator winding with compact coils includes use of an insertion winder. Other types and techniques known to those in the art to provide the stator windings 112 of the stator 20 can be used.

[0032] As discussed earlier, the drive circuit 125 can estimate the rotor 15 position through what is commonly referred as sensorless control. Sensorless motor commutation is often performed by sensing the back electromotive force (BEMF) produced by the motor 10. Typically, the BEMF signal produced in the stator windings 112 is not large enough for sensorless motor commutation until the speed of the rotor 15 reaches about ten percent of the rated motor 10 speed. Described below is one starting procedure for starting a BLDC motor 10 utilizing sensorless control.

[0033] The starting procedure is described below in three sections. The first section is a rotor position detection section. The second section is an initial pulsing section. The last section is a low-speed BEMF detection section. The starting procedure is stored as software instructions in memory 170. The processor 165 reads the instructions from memory 170, interprets the instructions, and executes the interpreted instruction resulting in the operation of the motor 10 as described below. Of course, other circuit components (e.g., an ASIC) can be used in place of the processor 165 and memory 170 to control the motor 10.

[0034] *A. Initial Rotor Position Detection*

[0035] The initial position detection of the rotor 15 is based on a more simplified version of U.S. Patent No. 5,001,405 (the '405 Patent). The '405 Patent describes a method of exciting one phase of a three phase motor with one polarity, and then, exciting the same phase with the opposite polarity. Through a comparison of the peak current, the rotor position is known within 60 degrees.

[0036] The starting algorithm employed within one construction of the invention does not excite the winding with the opposite current. This reduces the initial position resolution to 120 degrees (for a three-phase motor). Using this more simplified method with the other sections provides enough information to get the motor 10 started in the correct direction.

[0037] In one construction, the controller 160 uses the following pulse sequence:

Pulse [0]=Aon, Bdc, Coff (current goes in phase B and returns in phase A);
Pulse [1]=Adc, Boff, Con (current goes in phase A and returns in phase C); and
Pulse [2]=Aoff, Bon, Cdc (current goes in phase C and returns in phase B);

where dc represents a pulsed bus voltage, on represents the phase being grounded, and off represents no current in the winding (see Fig. 8). The current is measured at the end of each pulse. The sequence with the greatest current determines the rotor position and which phase to apply the first pulse movement.

[0038] In another construction, the controller 160 uses the following pulse sequence:

PulseParallel [0]=Aon, Bdc, Cdc (current goes in phase B and returns in phases A and C);
PulseParallel [1]=Adc, Bdc, Con (current goes in phase A and returns in phase C and B); and
PulseParallel [2]=Adc, Bon, Cdc (current goes in phase C and returns in phase B and A);

where dc represents a pulsed bus voltage and on represents the phase being grounded. The current is measured at the end of each pulse. The sequence with the greatest current determines the rotor position and which phase to apply the first pulse movement.

[0039] The winding sequence with the highest current is the winding that has the magnet most aligned with the field created by the winding. It is assumed that the direction of the current is also the direction of the north pole created by the winding current. For the example shown in Figure 8, phase B has the magnet most aligned (PulseParallel [2]). Therefore, in a six-step commutation sequence, the next sequence to turn on is Commutation[0] or an intermediate sequence of Adc, Bon, Coff. Preferably, the durations of the initial rotor pulses are fast enough and the current level is small enough to not cause the rotor 15 to move.

[0040] *B. Initial Pulsing*

[0041] An initial pulse, long enough to cause movement in the rotor 15, is applied to the appropriate phase from the information gathered from the previous section. The duty cycle or voltage applied to the winding 112 is set during the initial pulse such that the voltage for the phase that is open can be amplified to a level that movement is detected by monitoring a change in the voltage. If the initial pulsed voltage is too large then the motor accelerates too fast causing a torque transient that results in an undesirable audible noise at start. If the initial pulsed voltage is too small then there might not be enough torque to cause movement in the rotor. The initial movement of the rotor 15 depends on where the rotor 15 is positioned within the 120 degree window. Sampling BEMF at the start of the pulse gets a baseline voltage before movement has occurred. The BEMF is then monitored for a change in voltage, which is related to rotor movement. During the initial pulse sequence, the rotor 15 can actually move backwards before it moves forward. If this occurs, the controller 160 applies a breaking pulse to stop or slow the rotor movement, and the controller 160 returns to the previous section.

[0042] *C. Coast; sense BEMF crossings (low speed BEMF detection method)*

[0043] Once movement is detected and all phases are turned off, the BEMF is monitored for phase crossings. The negative half of the BEMF is clamped by diodes in the inverter 150. A commutation point occurs when the BEMF phases intersect (see Fig. 9).

[0044] More specifically, the software monitors three parameters:

1) Aphase>Bphase
2) Bphase>Cphase
3) Cphase>Aphase

These parameters are used to decode the rotor commutation position as follows:

Aphase>Bphase	Bphase>Cphase	Cphase>Aphase	
TRUE	FALSE	FALSE	Commutation[0]
TRUE	TRUE	FALSE	Commutation[1]
FALSE	TRUE	FALSE	Commutation[2]
FALSE	TRUE	TRUE	Commutation[3]
FALSE	FALSE	TRUE	Commutation[4]
TRUE	FALSE	TRUE	Commutation[5]

[0045] At the first change in any of the three conditions, the software starts a timer, and then, subsequently looks for the next "proper" transition. This is to make sure the motor 10 is running in the proper direction. Upon the second change in BEMF condition, the software stops the timer and measures the period. The controller 160 then commutates the motor with the appropriate commutation phase sequence (assuming the rotor is rotating in the proper direction). The software keeps the phase on as specified by the previous period, while looking for a conventional BEMF zero-cross event. The motor 10 can then commutate as is conventionally known in the art. For example, the controller 160 can use a six-step control technique for driving the motor 10. An example six step phase sequence to commutate the motor is

Commutation [0]=Adc, Bon, Coff (current goes in phase A and returns in phase B);
Commutation [1] =Adc, Boff, Con (current goes in phase A and returns in phase C);
Commutation [2]=Aoff, Bdc, Con (current goes in phase B and returns in phase C);
Commutation [3] =Aon, Bdc, Coff (current goes in phase B and returns in phase A);
Commutation [4]=Aon, Boff, Cdc (current goes in phase C and returns in phase A);
Commutation [5] =Aoff, Bon, Cdc (current goes in phase C and returns in phase B);

where dc represents a pulsed bus voltage and on represents the phase being grounded.

CLAIMS:

1. A method of controlling an electrical machine comprising

a stator comprising a core and a plurality of windings disposed on the core in a three-phase arrangement, the three-phase arrangement comprising a first phase, a second phase, and a third phase having a first terminal, a second terminal, and a third terminal, respectively, and

a rotor disposed adjacent to the stator to interact with the stator, the method comprising:

applying a first pulsed voltage differential to the terminals resulting in a current from the second terminal to the first and third terminals, the first pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a first value having a relation to a current resulting from the first pulsed voltage differential,

applying a second pulsed voltage differential to the terminals resulting in a current from the first terminal to the second and third terminals, the second pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a second value having a relation to a current resulting from the second pulsed voltage differential,

applying a third pulsed voltage differential to the terminals resulting in a current from the third terminal to the first and second terminals, the third pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a third value having a relation to a current resulting from the third pulsed voltage differential, determining which of the first, second, and third values having a relation to the current has the largest magnitude,

applying a fourth pulsed voltage differential to the terminals based on the determining step, the fourth pulsed voltage differential resulting in movement of the rotor;

after the applying the fourth pulsed voltage differential step,

monitoring the BEMF of each of the first, second, and third phases to determine the direction of rotation of the rotor,

determining whether the rotor is rotating in a desired direction, and

electrically commutating the motor when the rotor is rotating in the desired direction.

2. A method as set forth in claim 1 and further comprising, between the applying the fourth pulsed voltage differential step and the monitoring step, monitoring the back electromotive force (BEMF) of the third phase to sense rotor movement.

3. A method as set forth in claim 1 wherein the magnitudes of the first, second, and third pulsed voltage differentials are approximately the same.

4. A method as set forth in claim 1 wherein the first value has a relation to a bus current resulting from the first pulsed voltage differential.

5. A method as set forth in claim 1 wherein the first value has a relation to a phase current resulting from the first pulsed differential.

6. A method as set forth in claim 1 wherein the applying the fourth pulsed voltage differential step and the monitoring step occur at least partially simultaneously.

7. A method as set forth in claim 1 and further comprising:

after the applying the fourth pulsed voltage differential step and the monitoring step, monitoring the BEMF of each of the first, second, and third phases to determine the speed of rotation of the rotor.

8. A method as set forth in claim 1 wherein monitoring the BEMF of each of the first, second, and third phases comprises monitoring for changes in at least one of the following conditions

whether the BEMF of the first phase is greater than the BEMF of the second phase, and

whether the BEMF of the second phase is greater than the BEMF of the third phase, and

whether the BEMF of the third phase is greater than the BEMF of the first phase; and

wherein the method further comprises determining the direction of rotation of the rotor based on the monitoring for changes step.

9. A method as set forth in claim 8 and further comprising:

after the fourth pulsed voltage differential step and the monitoring step, determining the speed of the rotor based on the monitoring for changes step.

10. A method as set forth in claim 9 wherein commutating the rotor is based on the speed of the rotor.

11. A method of controlling an electrical machine comprising

a stator comprising a core and a plurality of windings disposed on the core in a three-phase arrangement, the three-phase arrangement comprising a first phase, a second phase, and a third phase having a first terminal, a second terminal, and a third terminal, respectively, and a rotor disposed adjacent to the stator to interact with the stator, the method comprising:

applying a first pulsed voltage differential from the second terminal to the first terminal, the first pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a first value having a relation to a current resulting from the first pulsed voltage differential,

applying a second pulsed voltage differential from the first terminal to the third terminal, the second pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a second value having a relation to a current resulting from the second pulsed voltage differential,

applying a third pulsed voltage differential from the third terminal to the second terminal, the third pulsed voltage differential resulting in substantially no movement of the rotor,

acquiring a third value having a relation to a current resulting from the third pulsed voltage differential,

determining which of the first, second, and third values having a relation to the current has the largest magnitude;

applying a fourth pulsed voltage differential to the terminals based on the determining step, the fourth pulsed voltage differential resulting in movement of the rotor;

after applying the fourth pulsed voltage and monitoring the BEMF,

monitoring the BEMF of each of the first, second, and third phases;

monitoring for changes in at least one of the following conditions

whether the BEMF of the first phase is greater than the BEMF of the second phase,

whether the BEMF of the second phase is greater than the BEMF of the third phase, and

whether the BEMF of the third phase is greater than the BEMF of the first phase;

determining the direction of rotation of the rotor based on the monitoring for changes step;

determining whether the rotor is rotating in a desired direction; and

electrically commutating the motor when the rotor is rotating in the desired direction.

12. A method as set forth in claim 11 and further comprising:

after applying the fourth pulsed voltage differential and monitoring the BEMF, determining the speed of the rotor based on the monitoring for changes step.

13. A method as set forth in claim 11 wherein the magnitudes of the first, second, and third pulsed voltage differentials are approximately the same.

14. A method as set forth in claim 11 wherein the first value has a relation to a bus current resulting from the first pulsed voltage differential.

15. A method as set forth in claim 11 wherein the first value has a relation to a phase current resulting from the first pulsed differential.

16. A method as set forth in claim 11 wherein applying the fourth pulsed voltage and monitoring the BEMF to sense rotor movement occurs at least partially simultaneously.

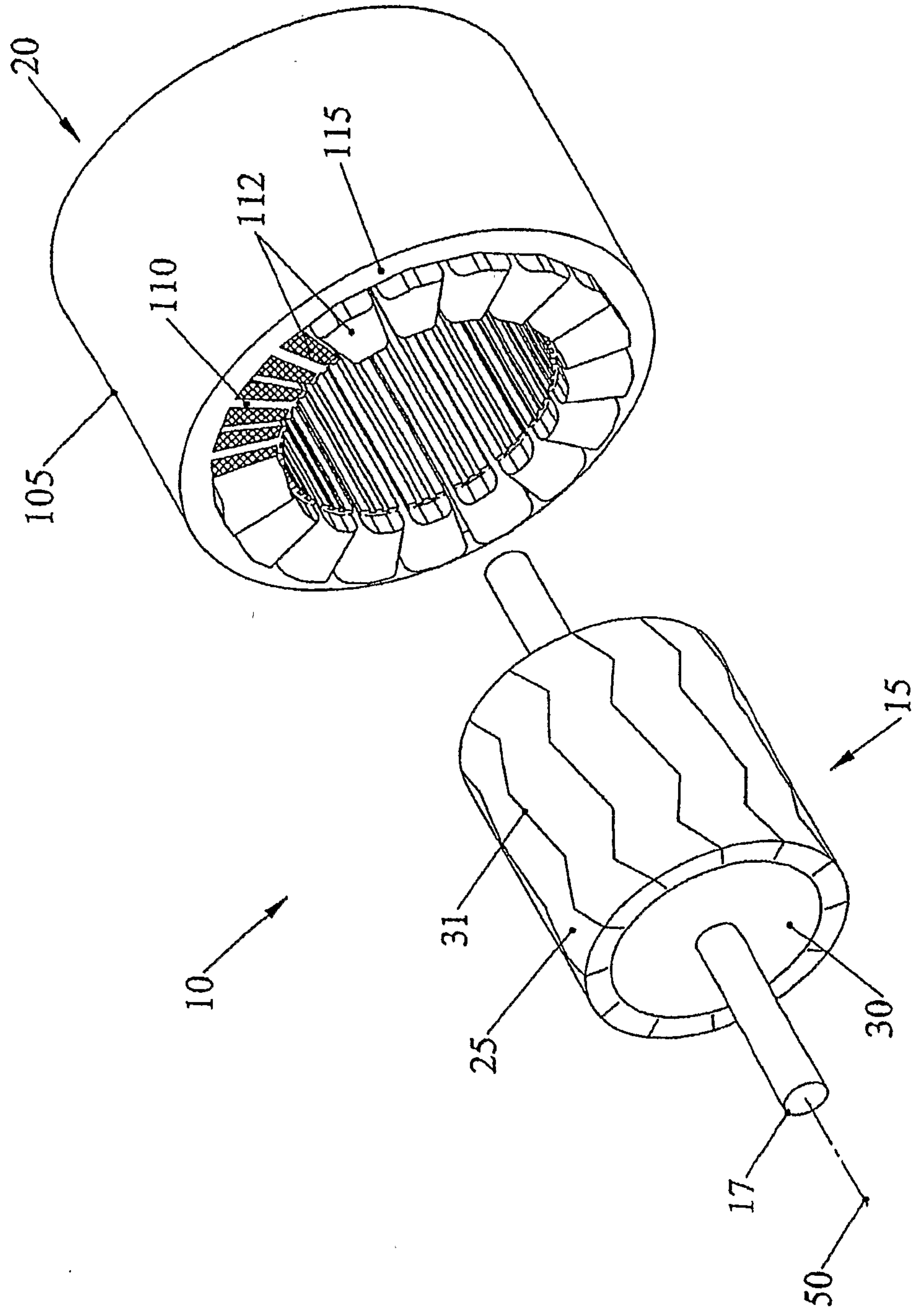


Fig. 1

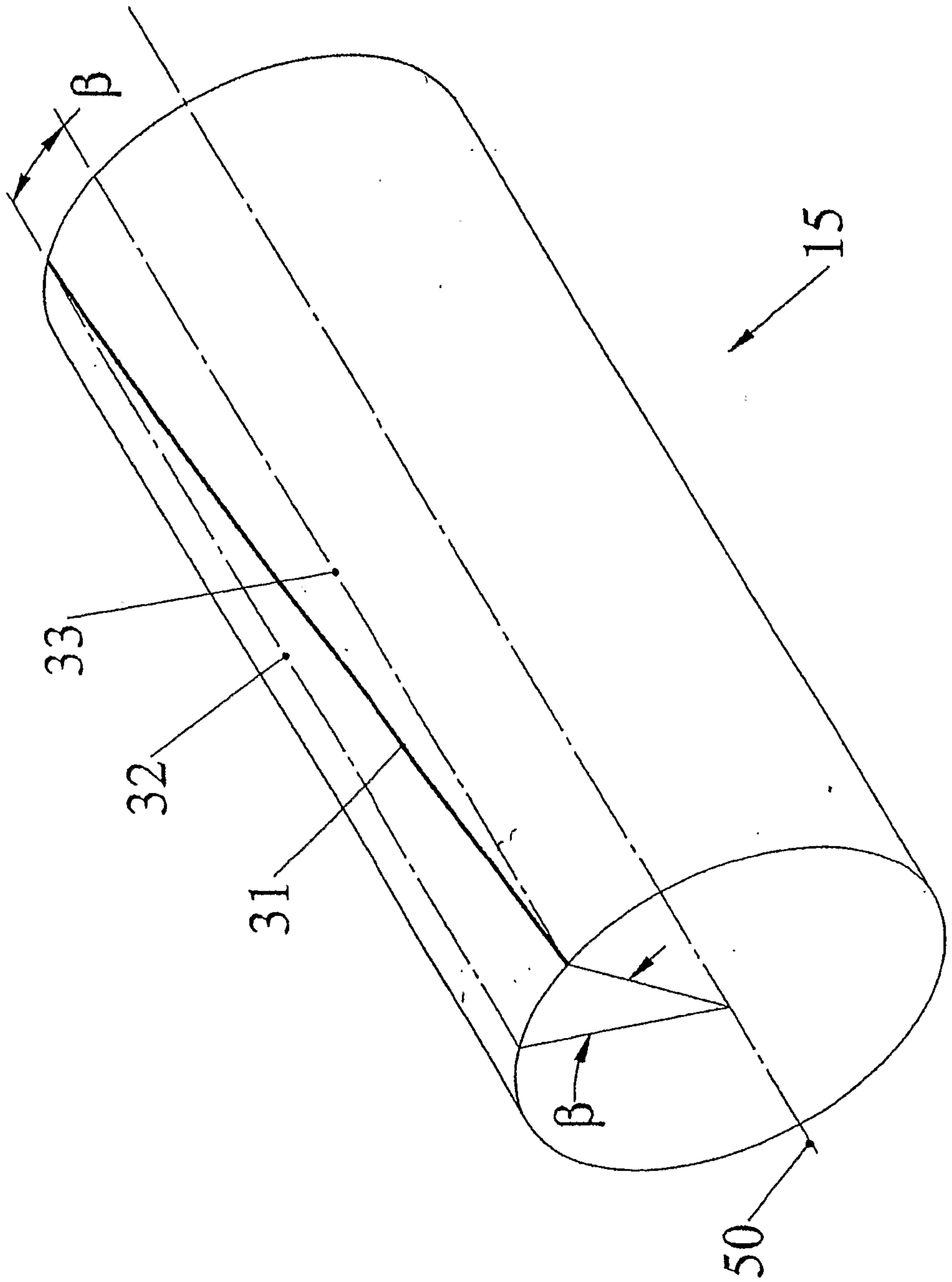


Fig. 2

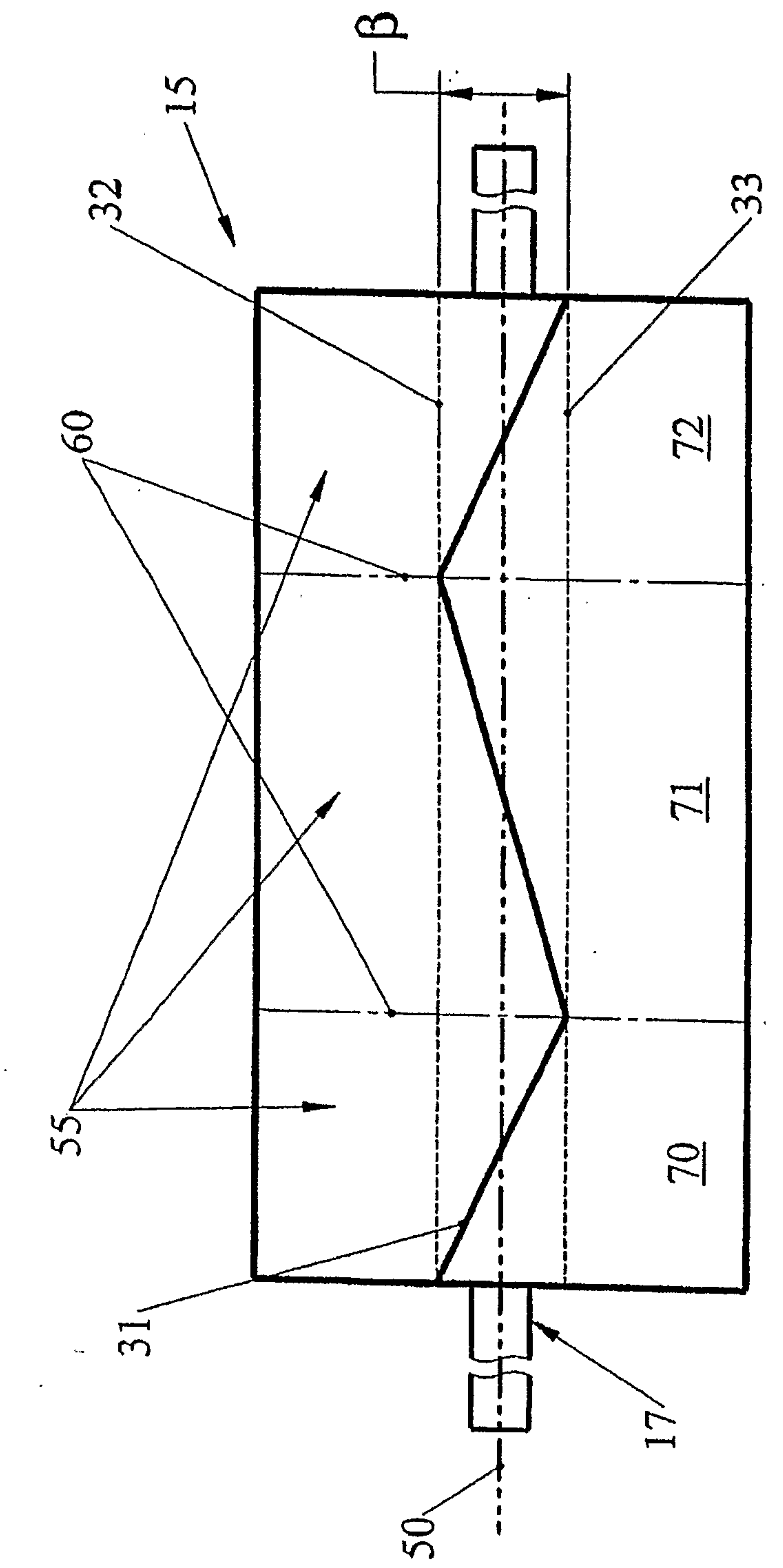


Fig. 3

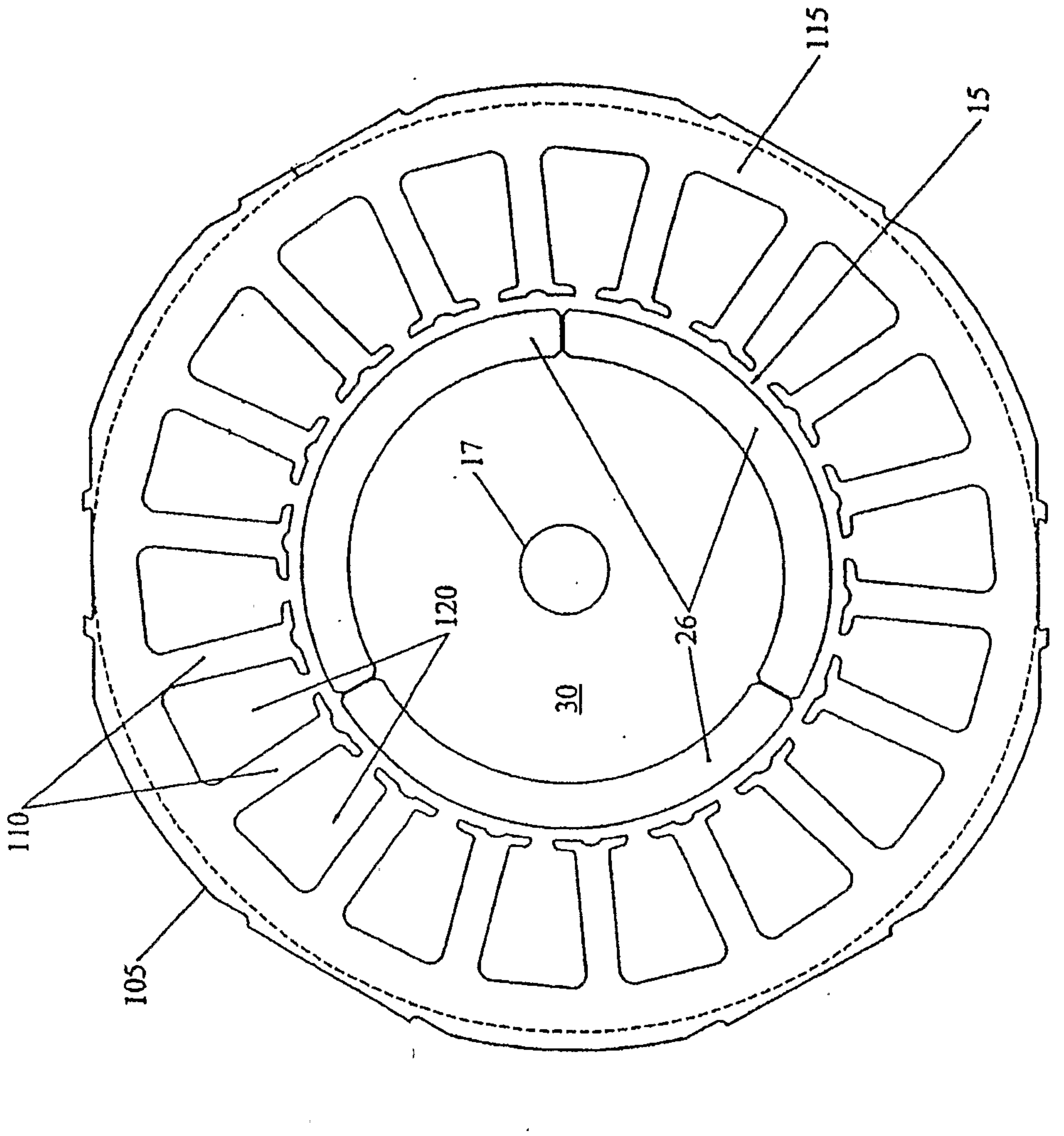


Fig. 4

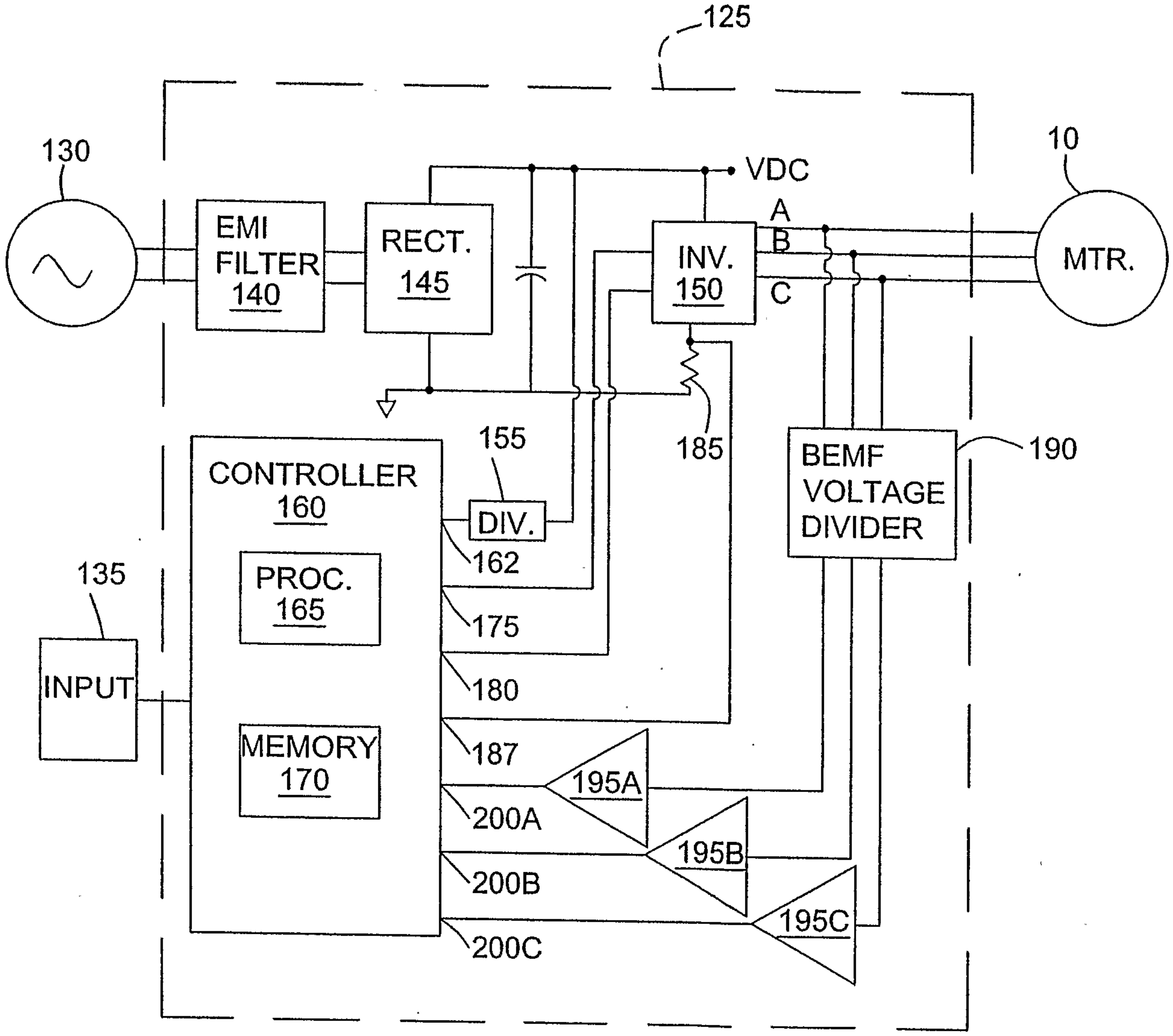

125
130
10
VDC
A
B
C
EMI FILTER 140
RECT. 145
INV. 150
MTR.
185
155
CONTROLLER 160
DIV.
162
PROC. 165
175
180
187
MEMORY 170
135
INPUT
BEMF VOLTAGE DIVIDER
190
195A
195B
195C
200A
200B
200C

FIG. 5

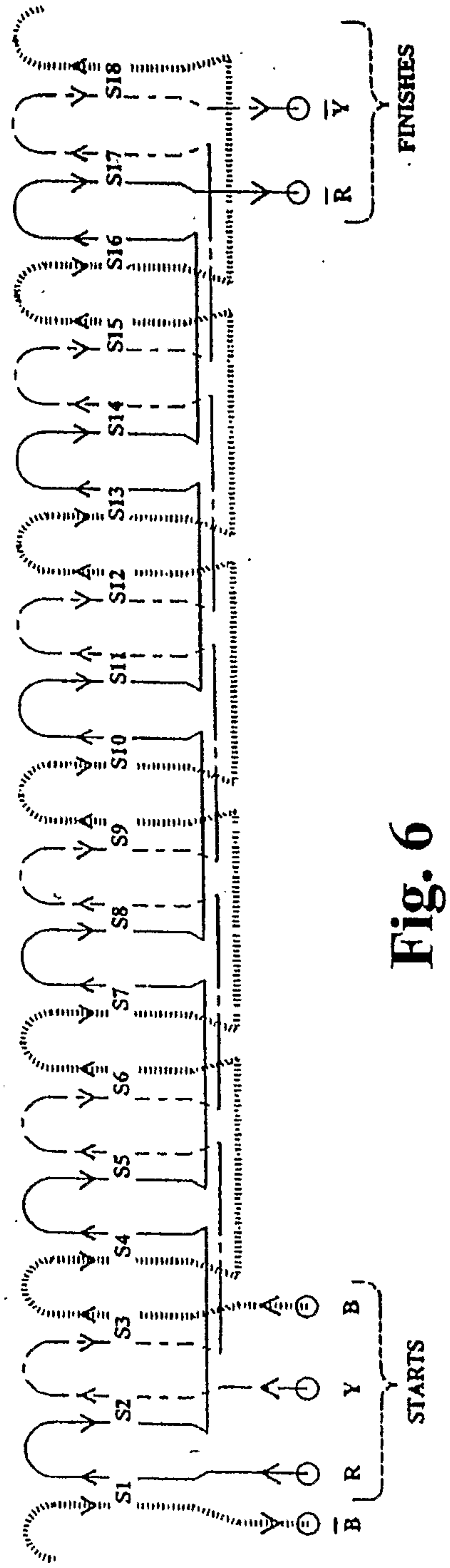

S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
R
Y
B
B̄
R̄
Ȳ
STARTS
FINISHES

Fig. 6

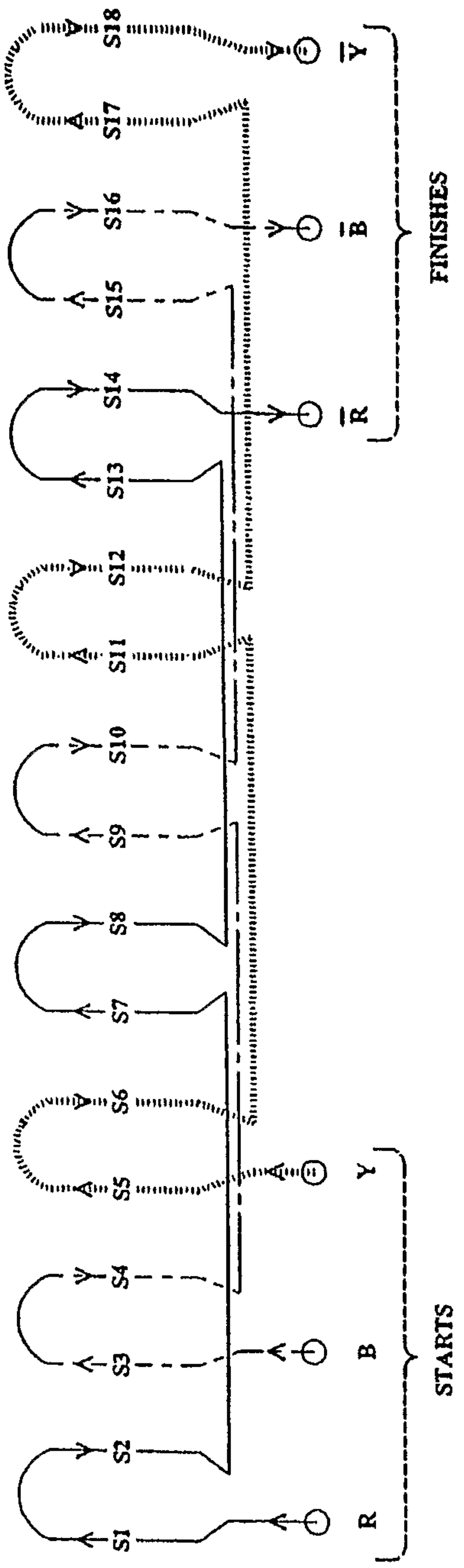

S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
R
B
Y
R̄
B̄
Ȳ
STARTS
FINISHES

Fig. 7

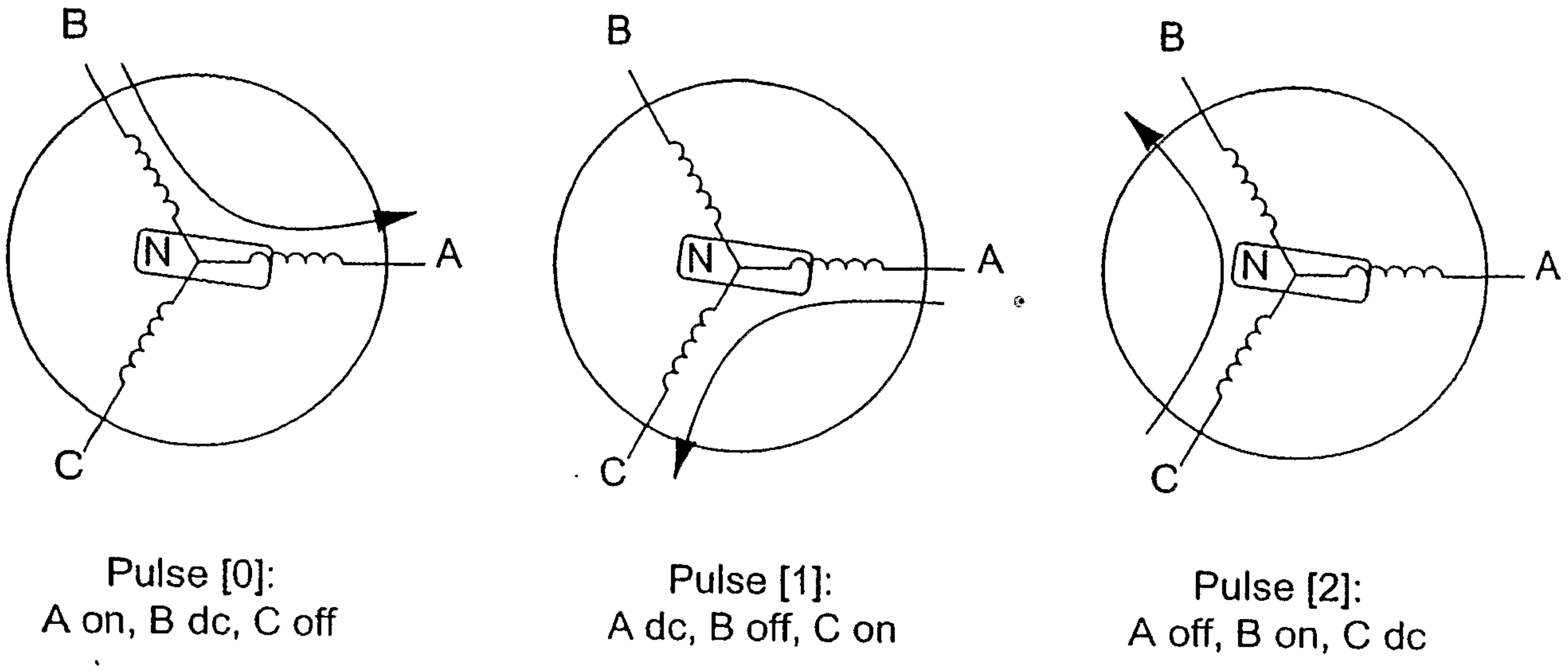

B
N
A
C
Pulse [0]:
A on, B dc, C off
B
N
A
C
Pulse [1]:
A dc, B off, C on
B
N
A
C
Pulse [2]:
A off, B on, C dc

FIG. 8

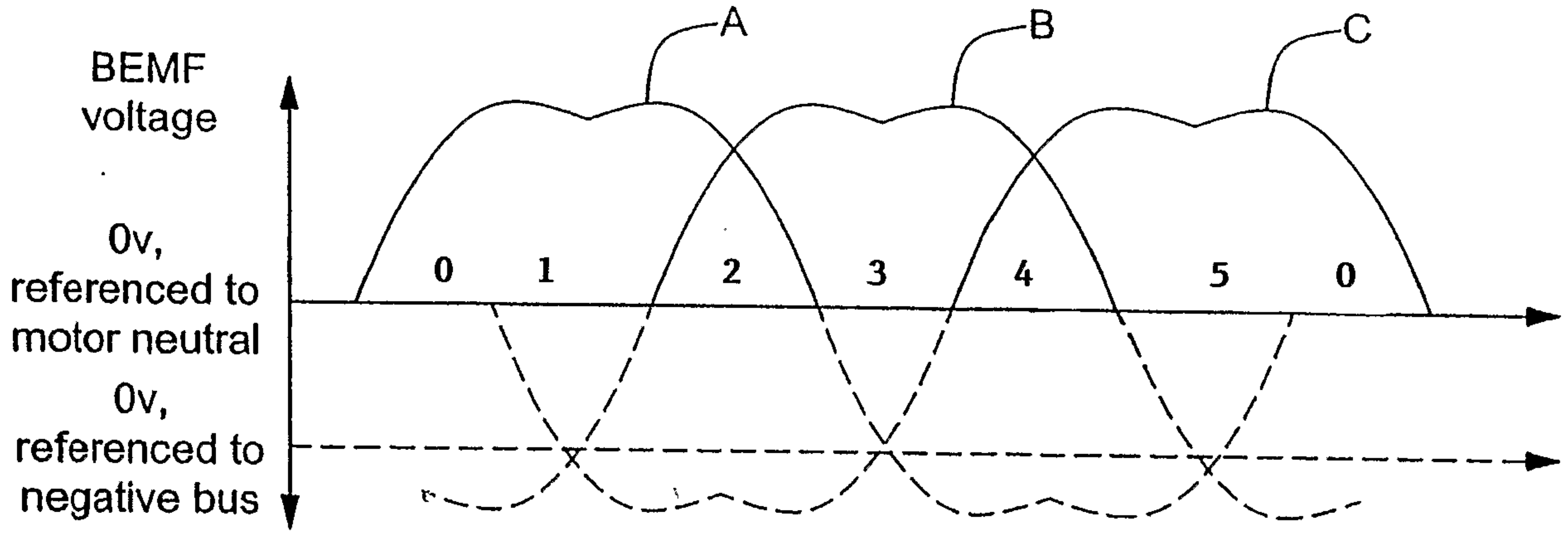
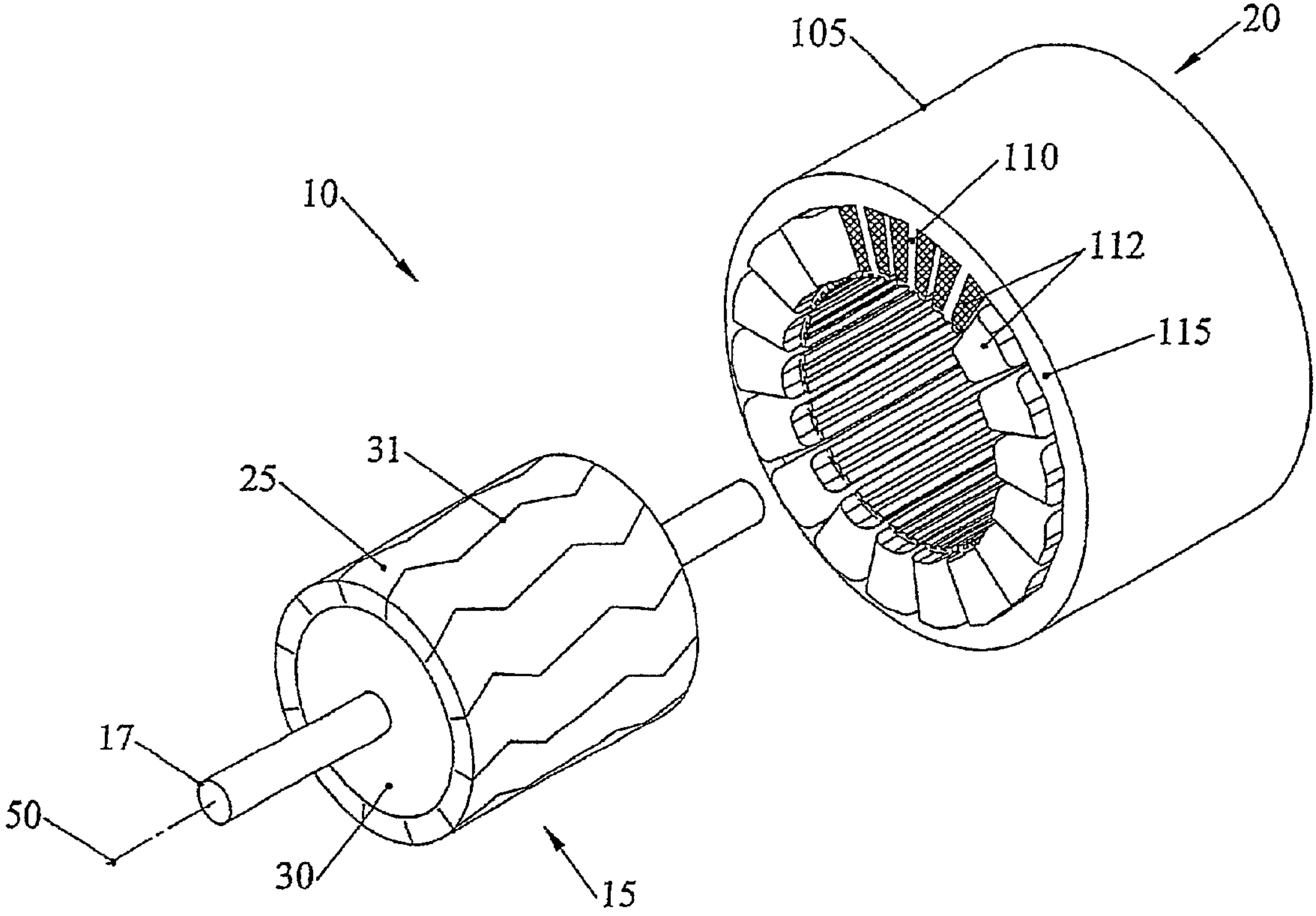

A
B
C
BEMF voltage
0v, referenced to motor neutral
0v, referenced to negative bus
0
1
2
3
4
5
0

FIG. 9


20
105
110
10
112
115
31
25
17
50
30
15