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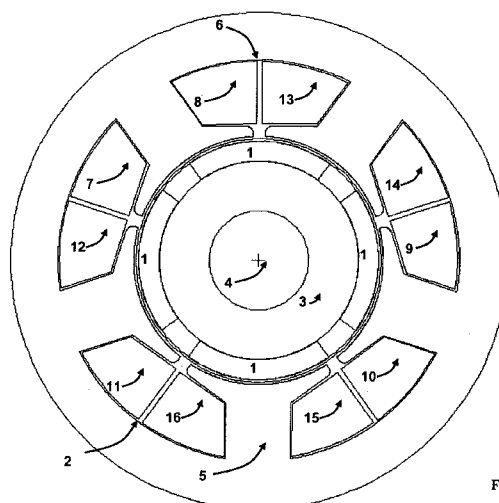


Fig. 1

(57) Abstract: A five-phase electrical machine comprises a first member and a second member, wherein: - one of the first member and the second member is arranged to be operable as a rotor and the other of the first member and the second member is arranged to be operable as a stator; the first member comprises a plurality of poles; and the second member comprises a plurality of teeth separated by slots, and five windings each for generation of one of the five phases, each winding comprising n connected coils where n is an integer, and each coil being wound around a respective single one of the teeth.

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An Electrical Machine

The present invention relates to the field of electrical machines, such as generators or motors. The invention relates, for example, to the field of permanent magnet machines
5 where a field excitation is provided by permanent magnets mounted on the rotor and where the electrical energy is generated in a set of multi-phase windings mounted in stator slots.

Background of the Invention

10 Electrical power generation can be performed by a variety of electromechanical conversion devices, which include devices such as the induction machine, the synchronous machine and the dc machine.

15 In general, known devices for industrial applications are three-phase machines. The electrical energy made available by large-scale electricity generation is three-phase, and generally is produced using a three-phase synchronous generator.

20 However, three-phase machines are not fault-tolerant. If one of the phases fails or is interrupted, a three-phase machine will fail or will operate at greatly reduced efficiency. Such lack of fault-tolerance can be particularly problematic if a three-phase machine is used as a generator for renewable energy applications, for example in a wave-power apparatus or wind turbine apparatus, and the generator is located in an inaccessible or remote location making maintenance difficult.

25 Furthermore, three-phase generators produce significant torque ripple effects, which can produce reduced efficiency, mechanical wear and ripple effects in the electrical output. Such torque ripple effects can be particularly problematic when the mechanical input to the generator is not constant but instead varies significantly over time, as is the case in
30 wave-power apparatus, wind turbine apparatus or other renewable energy apparatus.

Three-phase generators are best suited to systems in which the mechanical input to the system does not vary significantly over time, and which for example have a steady frequency. The three-phase output in turn then has a steady frequency and can be

passed, with little or no modification to its waveform, to the electrical grid or to a device to be powered. In general, three-phase generators are designed to ensure that the output waveforms of the three-phases approximate as closely as possible to sinusoidal waveforms.

5

In the case of wave-power, wind turbine or other renewable energy systems in which the frequency and amplitude of the mechanical input can vary significantly over time, the outputs from an associated electrical generator vary significantly in frequency and amplitude over time. In light of such variations, in some known systems the output from the generator is passed through diode rectification circuitry to convert it to d.c. before, in some cases, being converted back to a.c. using an inverter. Therefore it would be desirable to provide an electrical machine, for example a motor or generator, that is suitable for use with diode rectification circuitry and that can cope with significant variations in frequency and amplitude.

10

It is an aim of the present invention to provide an improved or at least alternative electrical machine.

Summary of the Invention

15

In a first independent aspect of the invention there is provided a five-phase electrical machine, comprising a first member and a second member, wherein:- one of the first member and the second member is arranged to be operable as a rotor and the other of the first member and the second member is arranged to be operable as a stator; the first member comprises a plurality of poles; and the second member comprises a plurality of teeth separated by slots, and five windings each for generation of one of the five phases, each winding comprising n connected coils where n is an integer, and each coil being wound around a respective single one of the teeth.

20

The machine may comprise 5n slots and 4n poles, where n is an integer, wherein:- each coil of a winding for one of the five phases is separated from a corresponding coil of the winding of the next of the five phases by c teeth, where c is an integer and satisfies the equation $c = \left(\frac{2}{5} + 2m \right) \frac{N_s}{N_r}$, where N_s is the number of slots, N_r is the number of poles

25

30

and m is an integer; each of the windings comprises a respective output, and each of the outputs is connected to a respective input of a five-phase diode rectifier bridge circuit; the five-phase diode rectifier bridge circuit comprises a plurality of output terminals, and a capacitance is connected between the output terminals; and each of the poles
 5 comprises at least one permanent magnet.

By providing such a five-phase electrical machine, improved fault tolerance, reduced torque ripple and higher efficiency of operation may be provided. For example, the electrical machine may provide improved output characteristics in comparison with
 10 known designs if one phase of the machine, or of the diode rectifier, fails to open circuit. Such fault tolerant operation can be significant for many applications, in particular when the machine is in a remote or inaccessible location and maintenance is difficult.

In addition, it has been found that such a five-phase electrical machine can provide
 15 output waveforms that are particularly suitable for conversion to d.c. by diode rectifier circuitry.

The five-phase design, and short pitched arrangement, may also provide for improved material utilisation, which can lead to higher torque per ampere values.
 20

The n coils for each winding may be equally spaced from one another. Each winding may be arranged to provide a respective one of the five phases.

The machine may comprise 5n slots and 4n poles, where n is an integer. For each
 25 winding the n coils may be separated by five teeth.

Each coil of a winding for one of the five phases may be separated from a corresponding coil of the winding of the next of the five phases by three teeth.

30 Each coil of a winding for one of the five phases may be separated from a corresponding coil of the winding of the next of the five phases by c teeth, where c is an integer and satisfies the equation $c = \left(\frac{2}{5} + 2m \right) \frac{N_s}{N_r}$, where N_s is the number of slots, N_r is the number of poles and m is an integer.

Each of the windings may comprise a respective output, and each of the outputs may be connected to a respective input of a five-phase diode rectifier bridge circuit.

- 5 The arrangement of slot number, coil winding pitch and distribution may be particularly suitable for connection of the machine to a five-phase diode rectifier in order to generate electrical energy, and may lead to reduced torque-ripple and vibration, improved fault tolerance and increased efficiency. The reduction in torque ripple may result in reduced mechanical vibration leading to reduced fatigue loading and extended lifetime and
10 reliability.

It has been found that in operation the output signals from the windings can be particularly suitable for conversion to d.c. by the diode rectifier circuitry. The electrical machine may be arranged so that the output signal from each winding varies in a
15 repeating cycle, with the amplitude of the output signal from each winding having a maximum and minimum value during each cycle. The electrical machine may be arranged so that the output signal for each winding has a flat-topped waveform in which its amplitude is substantially equal to the maximum or minimum value for extended periods in comparison to the case for a sinusoidal waveform.

20 In certain embodiments, the electrical machine may be arranged so that during at least one or each cycle the amplitude of the output signal from each winding is substantially equal to its maximum or minimum value for that cycle for greater than at least 5% and/or greater than at least 10% of the duration of the cycle.

25 The electrical machine may provide improved performance in comparison to three-phase machines in generator systems that utilise, for example, low-cost diode rectifier circuits, as is the case in renewable or low-carbon electrical generation systems.

- 30 The five-phase diode rectifier bridge circuit may comprise a plurality of output terminals, and a capacitance may be connected between the output terminals.

The capacitance may reduce voltage ripple and provide energy storage to enable continuous operation if output power reduces temporarily.

The increased number of capacitor charge cycles that the five-phase machine delivers may reduce capacitance requirements. Significant size, weight and cost savings may thus be realised by reducing capacitor size leading to improved system power density.

5

For each winding the n coils may be connected in series. The windings may be connected in a star or mesh configuration. Alternatively, the windings may be not electrically connected together.

10 In operation there may be magnetic flux between the rotor and the stator, and the magnetic flux may be radially oriented. Alternatively or additionally, the magnetic flux may be axially oriented. In operation, the rotor may at least one of translate and rotate. Each of the poles may comprise at least one permanent magnet. Thus, brushes may not be needed, which may reduce wear and thus maintenance requirements.

15

In a further independent aspect of the invention there is provided a method of manufacture of an electrical machine comprising providing a first member and a second member, the first member comprising a plurality of poles and the second member comprising a plurality of teeth separated by slots, wherein the method further comprises
20 winding five windings onto the second member, each winding comprising n connected coils where n is an integer, and each coil being wound around a respective single one of the teeth.

In another independent aspect of the invention there is provided an electrical machine
25 substantially as described herein, with reference to the accompanying drawings.

Any feature in one aspect of the invention may be applied to another aspect of the invention, in any appropriate combination. For example, apparatus features may be applied as method features and vice versa.

30

Detailed Description of Embodiments

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

Figure 1 is a schematic diagram of an electrical machine according to one embodiment, which has five stator teeth and four rotor poles and is operable as a generator;

Figure 2 is a circuit diagram that shows five phase coils of the embodiment of Figure 1 connected in a star-connected arrangement with five output terminals of the machine;

Figure 3 is a circuit diagram that shows five phase coils of the embodiment of Figure 1 connected in a mesh-connected arrangement with the five output terminals of the machine;

Figure 4 is a graph of phase voltage versus time that illustrates the simulated phase voltage waveforms from the machine when it is rotated at a constant speed and illustrates the phase relationship between phase voltages generated by the machine;

Figure 5 is a graph of simulated non-adjacent line voltages generated by the machine as a function of time;

Figure 6 is a schematic circuit diagram that illustrates the connection of the machine in the star-connected arrangement to a five-phase diode rectifier circuit;

Figure 7 is a graph of simulated shaft torque generated by the five-phase machine of Figure 1 when connected as shown in Figure 6 and supplying a rated load connected to the output terminals of the rectifier circuit;

Figure 8 is a graph of phase current versus time, and shows the phase currents in the machine under the conditions described for Figure 7;

Figure 9 is a graph of rectifier output voltage versus time and illustrates the rectifier output voltage characteristics under the conditions described for Figure 7;

Figure 10 is a graph of cogging torque versus time produced by the machine of Figure 1;

Figure 11 is a graph of shaft torque versus time, and shows the shaft torque generated by the machine when it is connected to a rated load but has an open circuit failure in one of the phases;

Figure 12 is a graph of rectifier output voltage versus time and shows the rectifier output voltage of the machine under the conditions described for Figure 11;

Figure 13 is a graph of winding current versus time and shows the simulated phase currents in the machine for the conditions described for Figure 11;

Figure 14 is a schematic diagram that shows an alternative embodiment, which has twenty stator teeth and sixteen rotor poles;

Figure 15 is a schematic diagram of a three-phase generator in accordance with the prior art, which has eighteen stator poles and sixteen rotor poles;

Figure 16 is a graph of torque versus time, which provides a comparison of the generated output torque of the five-phase and three-phase generators shown in Figures 14 and 15 when one phase is open circuit and illustrates the improved torque output of the 5-phase generator compare to the three-phase generator; and

5 Figure 17 is a graph of voltage versus time that shows the voltage at the output terminals of the generator before and after a single open circuit failure in the five-phase and three-phase generators of Figures 14 and 15 when supplying a rated load through a diode rectifier circuit.

10 Figure 1 shows an electrical machine according to one embodiment. The machine comprises a rotor mounted on a rotor shaft 4, and a stator 5. In the embodiment shown, the rotor has four magnetic poles 1 and five stator slots 2. The rotor poles are mounted on the rotor, which is constructed from an axial stack of ferromagnetic laminations 3 that are mounted on the rotor shaft 4. A rotor pole is a magnet (for example a permanent
15 magnet, for example NdFeB or SmCo) mounted on the rotor, and a stator slot is an opening in the stator where one side of a winding is located.

The style of rotor shown in Figure 1 may be referred to as a surface-mount rotor as the magnetic poles 1 are mounted on the outer surface of the rotor. In alternative
20 embodiments, the poles 1 are located within the rotor laminations, and the rotor may be referred to as an interior permanent magnet rotor.

The stator 5 has five slots 2 and each slot can accommodate one or more coils, where each coil comprises one or more turns of wire. For example, as shown in Figure 1 two
25 coil sides 8, 13 are located in one of the slots 6.

In the embodiment of Figure 1, there are five phase windings, referred to as A, B, C, D and E, each comprising a single coil. Each phase coil has two sides, a go and a return side, each of which conducts current in an opposite axial direction to the other. Coil A
30 has a go side A 7 and a return side A' 8. Coil B has a go side B 9 and a return side B' 10. Coil C has a go side C 11 and a return side C' 12. Coil D has a go side D 13 and a return side D' 14. Coil E has a go side E 15 and a return side E' 16. In the embodiment of Figure 1, each coil is arranged as a concentrated (or short pitched) winding where the coil spans one stator tooth. The number of teeth (coil displacement), c, between

corresponding coils of each adjacent phase winding (for example, between corresponding coils of phase A and B) is given by equation (1).

$$(1) \quad c = \left(\frac{2}{5} + 2m \right) \frac{N_s}{N_r}$$

5

Where N_s is the number of stator slots, N_r is the number of rotor poles, and m is chosen to make c an integer.

10

In the embodiment of Figure 1, N_s is 5, N_r is 4 and if $m=1$ then $c=3$. Therefore there are three stator teeth between phase A and phase B windings, three stator teeth between phase B and Phase C windings, three stator teeth between phase C and phase D windings and three stator teeth between phase D and phase E windings. The coil displacement is measured in the same direction (whether in the clockwise or the counter-clockwise direction).

15

Each phase coil has a similar number of turns. The number of turns is chosen to provide a voltage from the machine required for a particular application, according to Faraday's Law. Increasing the number of turns increases the peak of the output voltage from each phase.

20

Figure 2 is a circuit diagram representing the embodiment of Figure 1. Each phase winding has two terminals; a positive and a negative terminal. For example, phase winding A has terminals A+ 19 and A- 20. The machine has five output terminals 21, 22, 23, 24, 25. In Figure 2, the five phase coil windings are arranged into a star winding configuration, in which five of the phase winding terminals are connected together at a common point 20. Alternatively, as shown in Figure 3, the phase windings can be connected in a mesh configuration.

In a further alternative arrangement, the five phase windings of the machine are connected neither in a star configuration nor in a mesh configuration. Instead there are no common connections between the five phases, and the five phases provide independent output voltages from each of the five pairs of phase output terminals A+, A-; B+, B-; C+, C-; D+, D-; E+, E-.

30

In one example the rotor of the embodiment of Figure 1 is connected to a mechanical prime mover (for example a wave- or wind- power device) and, in operation, the rotor is rotated relative to the stator by operation of the mechanical prime mover. The machine thus operates as a generator. When the rotor is rotated at a constant speed, the output voltages from each phase winding are phase displaced by either 72 electrical degrees or 144 electrical degrees from those from other phase windings depending on whether phases are adjacent or non-adjacent respectively. For example, the output voltage from phase A winding is phase displaced by 72 electrical degrees from the phase B and phase E windings, and the phase A winding is displaced from the phase C and phase D windings by 144 electrical degrees, as illustrated in Figure 4, which is a plot of output voltage (V_a , V_b , V_c , V_d , V_e) versus time for each of the five phases A, B, C, D and E. Non-adjacent output line voltages (for example, the voltage V_{ac} between terminals 21 and 22) are then balanced five-phase outputs and have a waveshape as illustrated in Figure 5.

The five output terminals can be connected to a five-phase diode rectifier circuit as shown in Figure 6. The diode rectifier has ten diodes 26-35 connected in a bridge arrangement. The output terminals of the rectifier 36 and 37 supply the rectified outputs from the generator and constitute a dc power source that can feed a load, for example, a DC power system or grid-connected inverter. A dc link capacitor 38 can be used to further smooth the output voltage. The capacitor 38 is omitted in alternative embodiments, as the five phase generator can itself provide a sufficiently smooth output for many applications.

It can be seen that by utilising short-pitched windings in a five-phase electrical machine where the phase coils are displaced according to the coil span equation (1) the machine can provide an output voltage whose shape is particularly suitable for input to a diode rectifier. The phase winding arrangement of the embodiment of Figure 1 generates an output phase voltage waveshape as shown in Figure 4 and an output line voltage (non adjacent phases, for example, the voltage V_{ac} between terminals 21 and 22) shown in Figure 5. It can be seen from Figure 4 that the waveform of the output voltage of each winding is relatively flat around the maximum and minimum values. The value of the voltage is substantially equal to its maximum or minimum value during a significantly

greater proportion of each cycle than is the case for sinusoidal waveforms, which makes the waveforms particularly suitable for conversion to d.c. by the diode rectifiers.

5 The winding arrangement described can result in a generator back emf that is particularly suitable for use with diode rectifiers. For example, torque ripple at the shaft of the generator can be reduced in the generator when the generator is connected to a diode rectifier (with or without a dc link capacitor).

10 Figure 7 shows simulated shaft torque when the embodiment of Figure 1 is connected to a diode rectifier circuit with a capacitor 38 of 100 μ F capacitance connected across the outputs 36, 37. Figure 7 illustrates the low value of torque ripple generated by the machine at full load. Figure 8 shows the resulting phase currents (i_a , i_b , i_c , i_d , i_e) in each of the phases of the machine when operating at full-load at a constant speed and when the generator feeds a diode rectifier circuit with associated load. Figure 9 illustrates the
15 output voltage between terminals 36,37 when the machine is operated at rated load. It can be seen that the ripple voltage is only about 0.5%.

The cogging torque for the embodiment shown in Figure 1 is detailed in Figure 10. In this embodiment the cogging torque is only 1.5% of rated torque (without any skewing on
20 either rotor or stator). In the embodiment shown the magnet arc is 120 electrical degrees. The magnet arc can be increased or decreased. It can be seen from Figure 10 that the embodiment of Figure 1, comprising five stator slots for each of the four rotor poles, demonstrates low cogging torque.

25 It has been found that by winding the machine in a short-pitched fashion with adjacent phase coils displaced according to equation (1), for example displaced by three slots in the embodiment of Figure 1, leads to a five-phase balanced output. It has been found for the described embodiments that the tolerance to open circuit failures in either the diodes of the diode rectifier, or of the machine itself, are improved compared to corresponding
30 three-phase designs having the same or similar numbers of rotor poles.

Figure 11 show simulated shaft torque of the embodiment of Figure 1, with five stator slots and four rotor poles, in the case where there is an open circuit failure of one of the phase windings. The shaft torque of the generator when connected to a diode rectifier is

reduced by around 11%. That drop is much less than a corresponding three-phase machine having the same number of rotor poles. The resulting voltage at the output of the diode rectifier (between terminals 36, 37) is illustrated in Figure 12. The DC voltage ripple (11% in the simulated case) is larger than in the healthy condition with all five phases functioning correctly (0.5%) but considerably improved when compared with an similarly-rated three-phase generator with one open circuit phase failure. Figure 13 shows the resulting phase currents (i_a , i_b , i_c , i_d , i_e) in the machine (which is connected in the star-connected arrangement of Figure 2). There are now only four non-zero phase currents as one phase of the machine is open-circuit, and therefore cannot provide any current or energy to the load.

A further embodiment of the invention is shown in Figure 14. In this embodiment the machine has twenty stator teeth and sixteen rotor poles and is wound with twenty short-pitched coils, which are located in the stator slots in a double layer configuration. The coils are positioned in accordance with equation (1), from which it is determined that the coil displacement is three (with $m=1$). Each of the phase windings comprises four of the short-pitched coils connected in series (although they can be connected in parallel in a variant of the embodiment). The first coil of phase winding A is located around tooth 41 and the second, third and fourth coils of winding A are located around teeth 42, 43, 44 respectively. The coils that are connected in series for phase winding B are located around stator teeth 45, 46, 47, 48. The coils that are connected in series for phase winding C are located around stator teeth 49, 50, 51, 52. For phase winding D the coils are located around stator teeth 53, 54, 55, 56. For phase winding E, the coils are located around stator teeth 57, 58, 59, 60. It can be seen from Figure 14 that the coils are located in accordance with the coil displacement determined from equation (1).

Figure 15 illustrates a three-phase generator that has sixteen poles and an equivalent speed rating to the generator of Figure 14. For such a three-phase generator, the optimum number of stator slots is eighteen so as to minimise cogging torque. The machine has six coils per phase, connected in series.

Figure 16 show simulation data for the five-phase and three-phase machines of Figures 14 and 15. In each case the machines have the same outer diameter and stack length, and the inside bore of the stator is the same. The waveforms shown in Figure 16 are of

the shaft torque generated by the machine when delivering power to a rated load via a diode rectifier circuit. During healthy conditions, when all phases in each machine are functioning correctly, it is clear that the torque ripple of the five-phase machine is significantly lower than that of the three-phase counterpart. During the simulation one phase of each machine is forced to an open circuit to simulate failure of one phase. It is clear from Figure 16 that the torque ripple for the five-phase machine is significantly lower than that of the three-phase machine, and also that the average torque generated by the five-phase machine is considerably greater than the three-phase machine. This means that the five-phase machine is capable of delivering more power during an open-circuit phase failure than the three-phase counterpart. Figure 17 demonstrates the impact that an open-circuit failure has on the output voltage of the diode rectifier during the open circuit failure. The output voltage from the rectifier that is fed from the three-phase machine falls considerably during the failure, whereas the five-phase output voltage does not fall as far. Furthermore the ripple in the output voltage for the five-phase case after the failure is small compared to that of the five-phase generator.

Permanent magnet generators according to embodiments of the invention may be connected to diode rectifier circuits in small-scale renewable power generators, for example. However, there are many other power generation applications for which the embodiments are particularly suitable. For example, embodiments can be used for the generation of electrical energy from mechanical energy. One example is in a wind turbine where the electrical generator converts the mechanical energy harnessed by an aerodynamic blade system into useful electrical energy. Another example is in hybrid electric vehicles, for example, for the conversion of mechanical output power of the internal combustion engine to electrical power which is then used to drive wheels or charge energy storage. There are aerospace applications, for example, conversion of mechanical power to electrical power in the auxiliary power unit on an aircraft, or as the main power generator in an unmanned vehicle. The technology suits a significant and diverse range of applications.

The embodiments shown in Figure 1 and Figure 14 comprise five-phase windings that have a ratio of stator teeth to rotor poles equal to $5/4$ and that are short-pitched windings. Other embodiments are of course possible that provide a five phase machine that has five stator windings comprising coils wound in a short pitched arrangement.

There are many different slot shapes that can be used to provide desired operating characteristics of the machine (for example, by reducing local magnetic saturation) and these are well known to those experienced in the art of electrical machine design.

5 Likewise, the rotor magnet shape, size and location can be changed or altered. The shape, size and position of the magnets shown in the embodiment are indicative, but not exclusive, and different magnet options are well known to those experienced in the design of permanent magnet machines.

10 Although the machine in the described embodiments is operated as a generator, other embodiments are operated as motors or other devices. In one embodiment, the machine is used as an electric motor in a hybrid vehicle.

In further embodiments, other machines or families are provided, each defined, in part,
15 by the ratio of stator slots to rotor poles. In addition, within each family of machines defined by ratio of stator slots to rotor poles, there are also a number of possible methods of winding the machine, in which 'go' and 'return' sides of each coil can be located across different numbers (or span) of stator slots, and in which more than one coil side can be located in each stator slot.

20

In addition to the radial flux machines illustrated in Figures 1 and 14, other alternative embodiments are axially-oriented flux rotational machines, or linear machines. In an axially-oriented flux machine, the flux vector in the air-gap that separates the moving member of the machine (for example, the rotor) from the stationary member of the machine (for example, the stator) is in the axial direction (parallel to the axis around
25 which the rotor rotates. In a radially-oriented flux machine, the flux vector in the air-gap is in the radial direction relative to the axis of rotation. In a linear machine, the moving member translates in a linear fashion rather than rotating as in a rotational machine. In such embodiments, the spacing between adjacent phase windings can be determined
30 according to equation (1). For example, five phase windings, short pitch coils, and five stator teeth for every four rotor poles are provided in some such further alternative embodiments.

It will be understood that the present invention has been described above purely by way

of example, and modifications of detail can be made within the scope of the invention.

Each feature disclosed in the description, and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination.

CLAIMS

1. A five-phase electrical machine comprising a first member and a second member, wherein:-

one of the first member and the second member is arranged to be operable as a rotor and the other of the first member and the second member is arranged to be operable as a stator;

the first member comprises a plurality of poles; and

- the second member comprises a plurality of teeth separated by slots, and five windings each for generation of one of the five phases, each winding comprising n connected coils where n is an integer, and each coil being wound around a respective single one of the teeth.

2. A machine according to Claim 1, comprising 5n slots and 4n poles, where n is an integer, wherein:-

wherein each coil of a winding for one of the five phases is separated from a corresponding coil of the winding of the next of the five phases by c teeth, where c is an integer and satisfies the equation $c = \left(\frac{2}{5} + 2m \right) \frac{N_s}{N_r}$, where N_s is the number of slots, N_r

- is the number of poles and m is an integer;

each of the windings comprises a respective output, and each of the outputs is connected to a respective input of a five-phase diode rectifier bridge circuit;

the five-phase diode rectifier bridge circuit comprises a plurality of output terminals, and a capacitance is connected between the output terminals; and

- each of the poles comprises at least one permanent magnet.

3. A machine according to Claim 1, comprising 5n slots and 4n poles, where n is an integer.

4. A machine according to any preceding claim, wherein for each winding the n coils are separated by five teeth.

5. A machine according to any preceding claim, wherein each coil of a winding for one of the five phases is separated from a corresponding coil of the winding of the next of the five phases by three teeth.

5 6. A machine according to any preceding claim, wherein each coil of a winding for one of the five phases is separated from a corresponding coil of the winding of the next of the five phases by c teeth, where c is an integer and satisfies the equation $c = \left(\frac{2}{5} + 2m \right) \frac{N_s}{N_r}$, where N_s is the number of slots, N_r is the number of poles and m is an integer.

10

7. A machine according to any preceding claim, wherein each of the windings comprises a respective output, and each of the outputs is connected to a respective input of a five-phase diode rectifier bridge circuit.

15 8. A machine according to Claim 7, wherein the five-phase diode rectifier bridge circuit comprises a plurality of output terminals, and a capacitance is connected between the output terminals.

20 9. A machine according to any preceding claim, wherein for each winding the n coils are connected in series.

10. A machine according to any preceding claim, wherein the windings are connected in a star or mesh configuration.

25 11. A machine according to any preceding claim, wherein the windings are not electrically connected together.

12. A machine according to any preceding claim, wherein in operation there is magnetic flux between the rotor and the stator, and the magnetic flux is radially oriented.

30

13. A machine according to any preceding claim, wherein in operation there is magnetic flux between the rotor and the stator, and the magnetic flux is axially oriented.

14. A machine according to any preceding claim, wherein in operation the rotor at least one of translates and rotates.

15. A machine according to any preceding claim, wherein each of the poles
5 comprises at least one permanent magnet.

16. A machine according to any preceding claim that is a motor or a generator.

10 17. A method of manufacture of an electrical machine comprising providing a first member and a second member, the first member comprising a plurality of poles and the second member comprising a plurality of teeth separated by slots, wherein the method further comprises winding five windings onto the second member, each winding comprising n connected coils where n is an integer, and each coil being wound around a respective single one of the teeth.

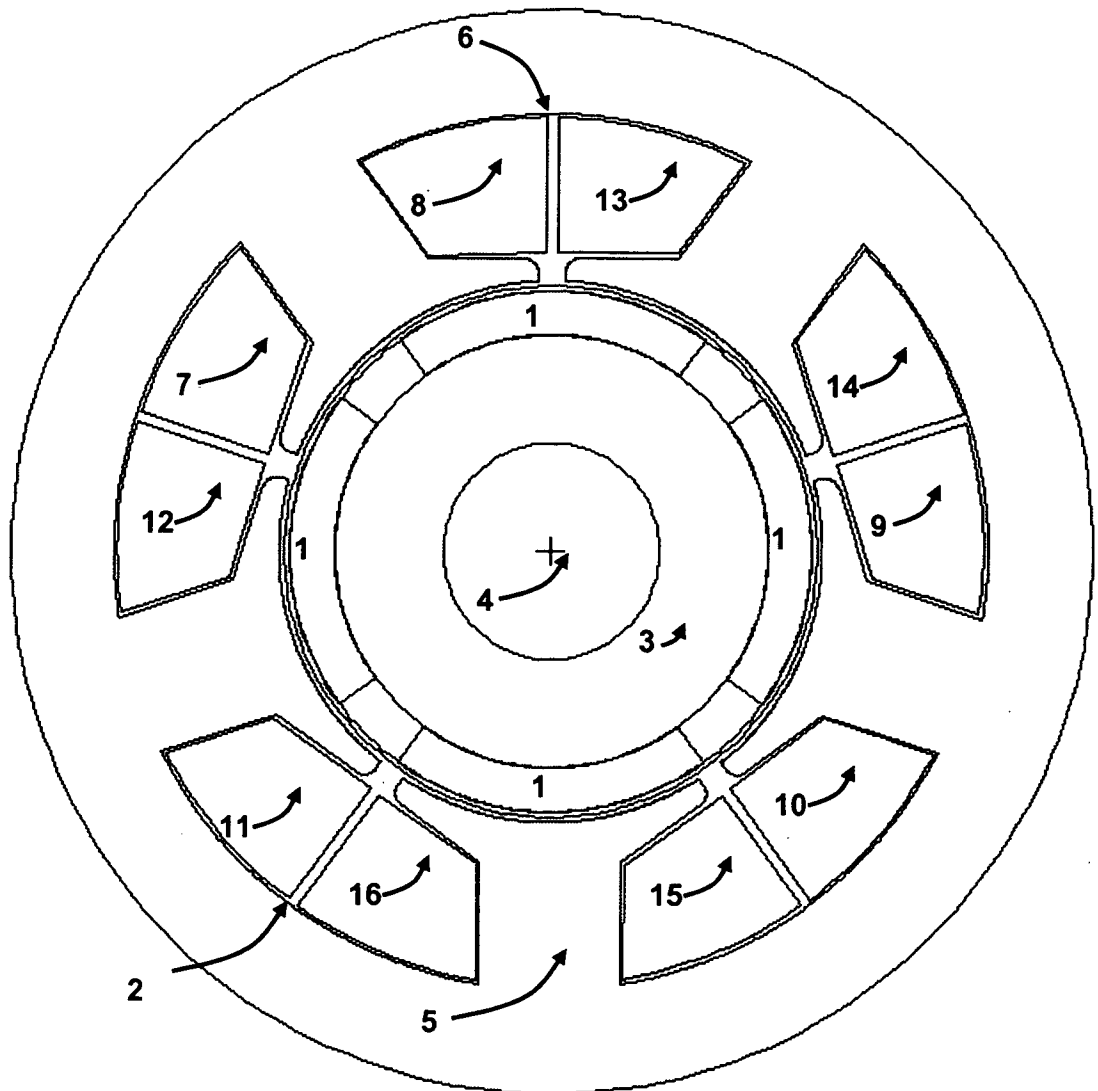


Fig. 1

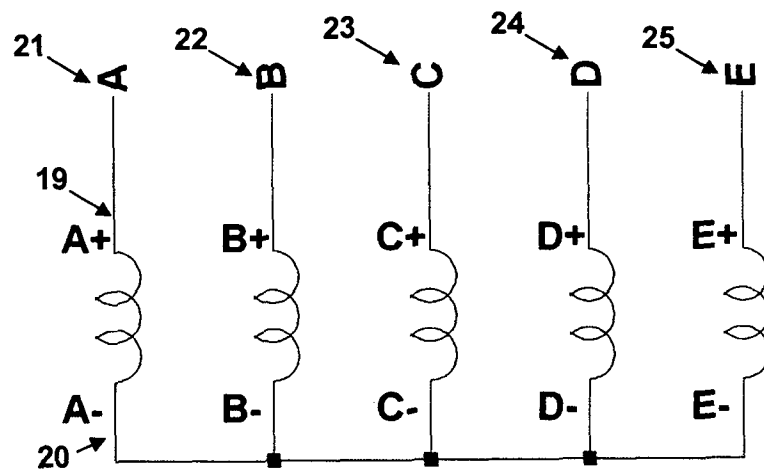


Fig. 2

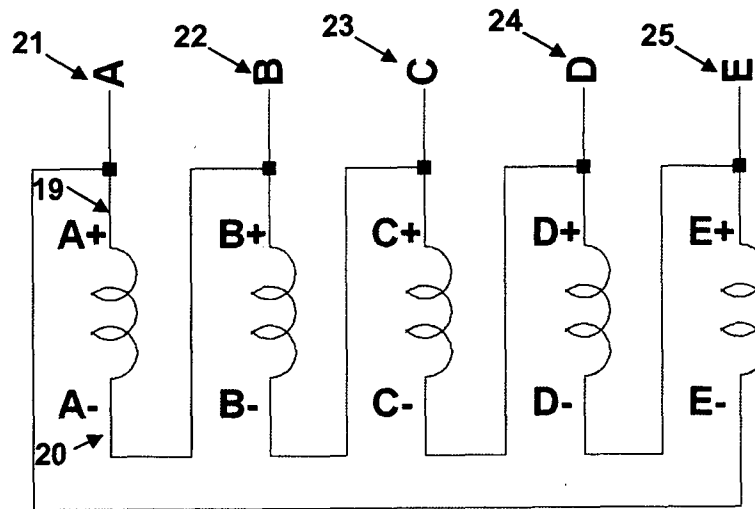


Fig. 3

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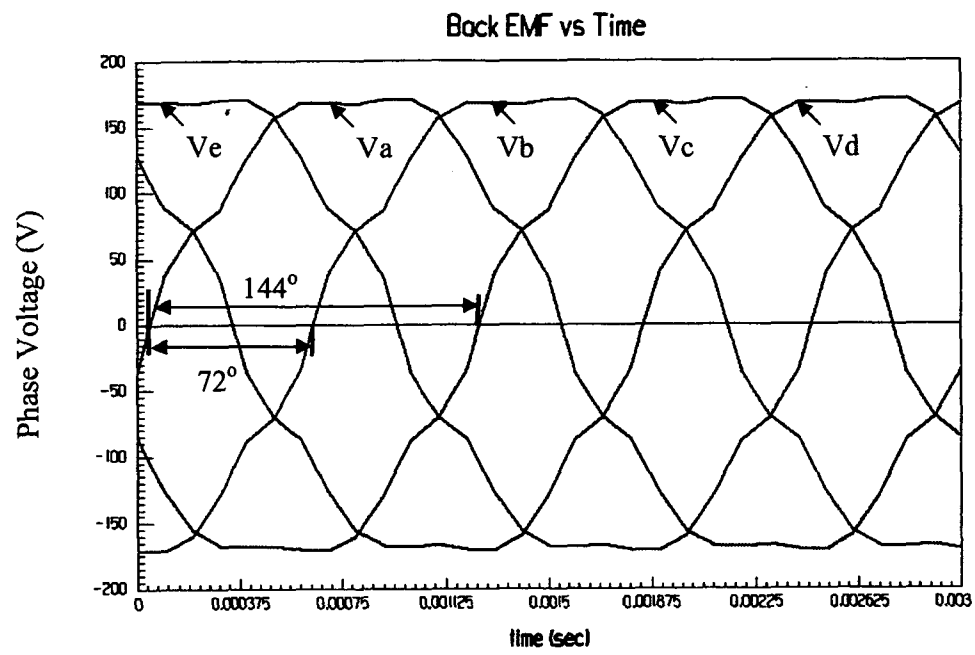


Fig. 4

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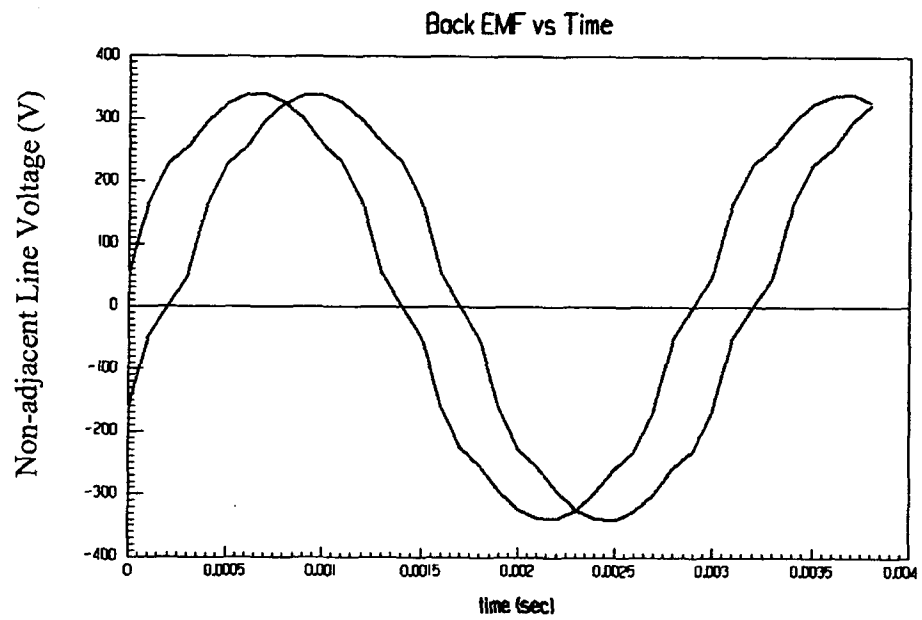


Fig. 5

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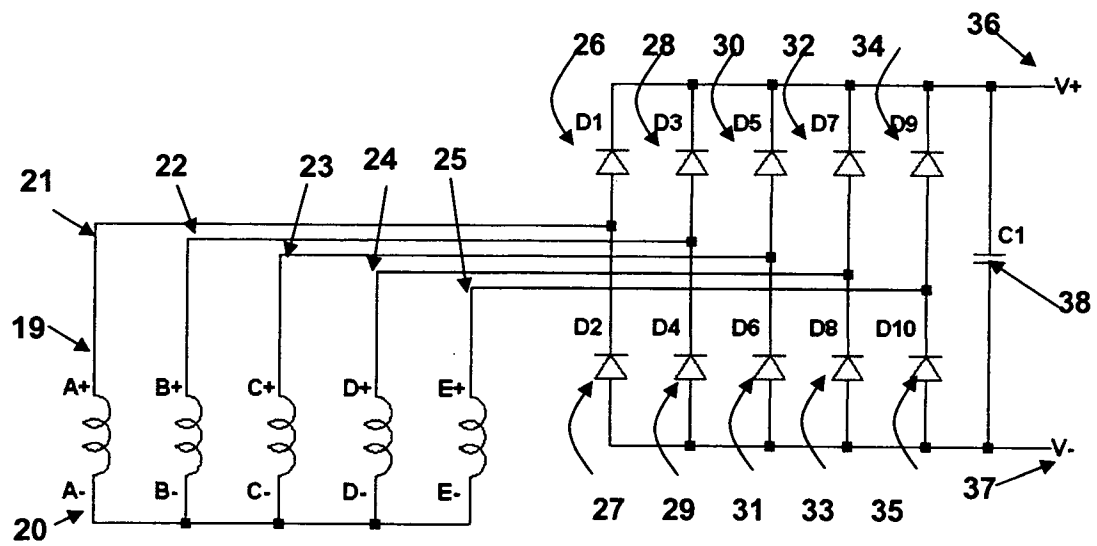
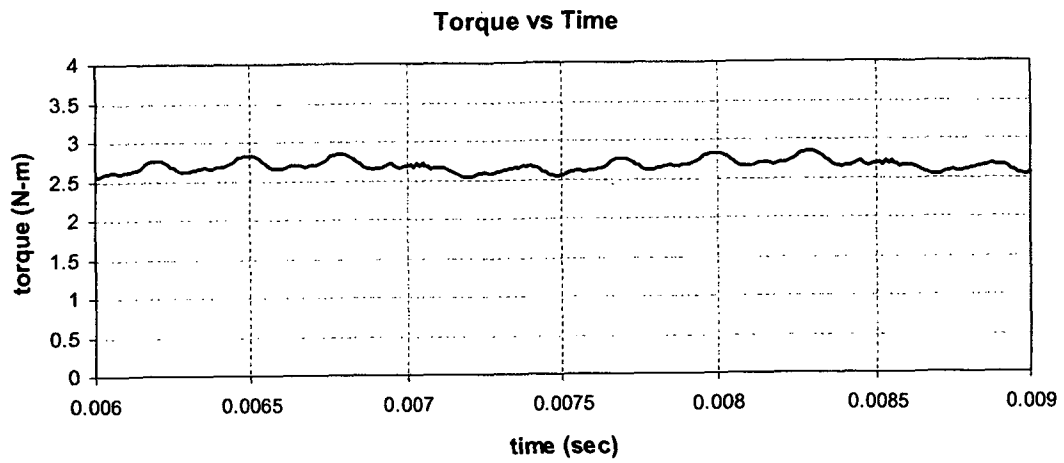


Fig. 6

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**Fig. 7**

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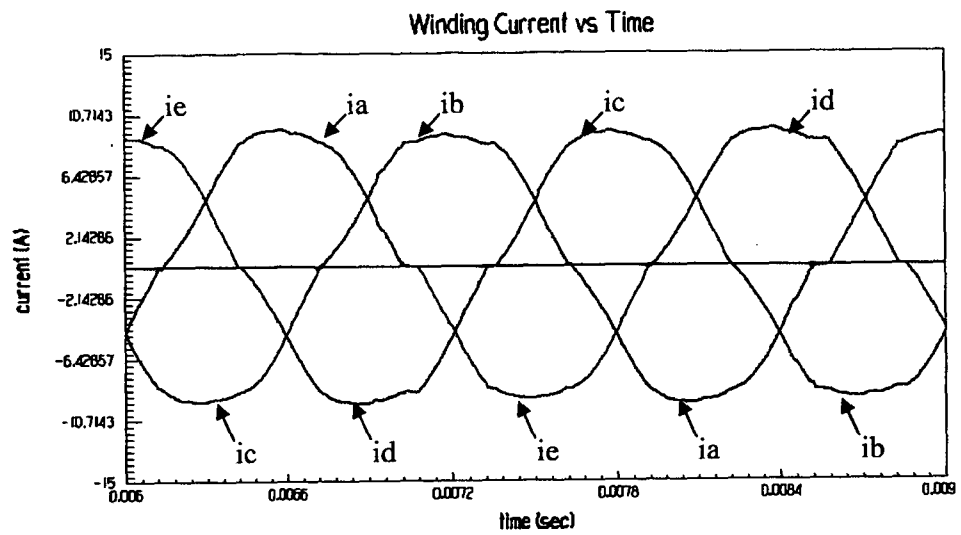


Fig. 8

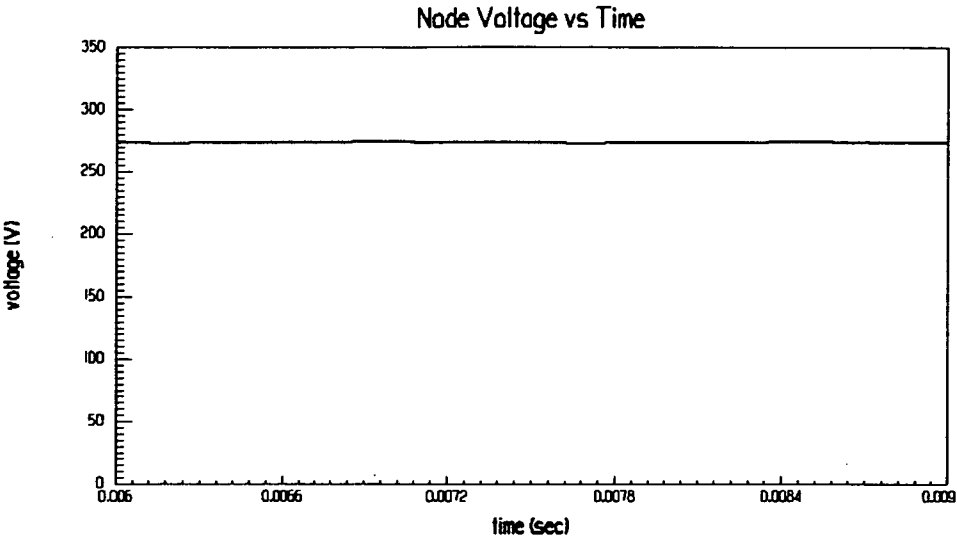


Fig. 9

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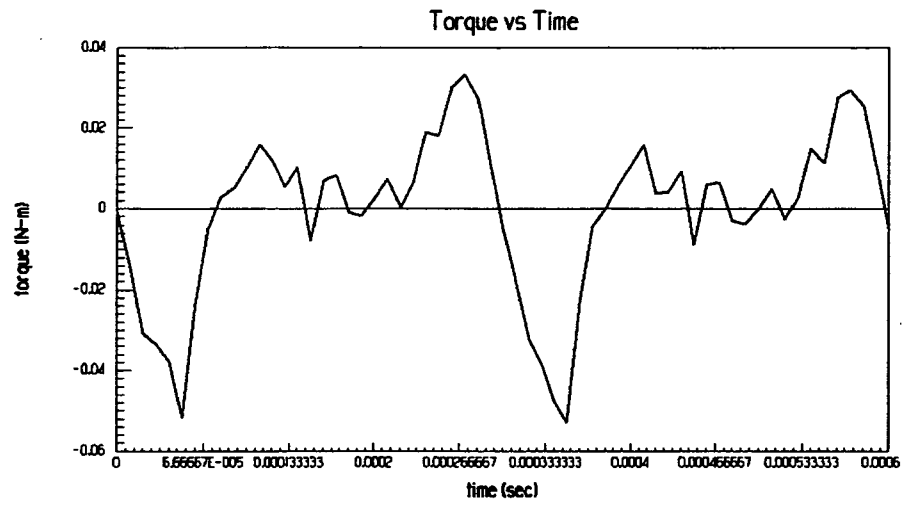
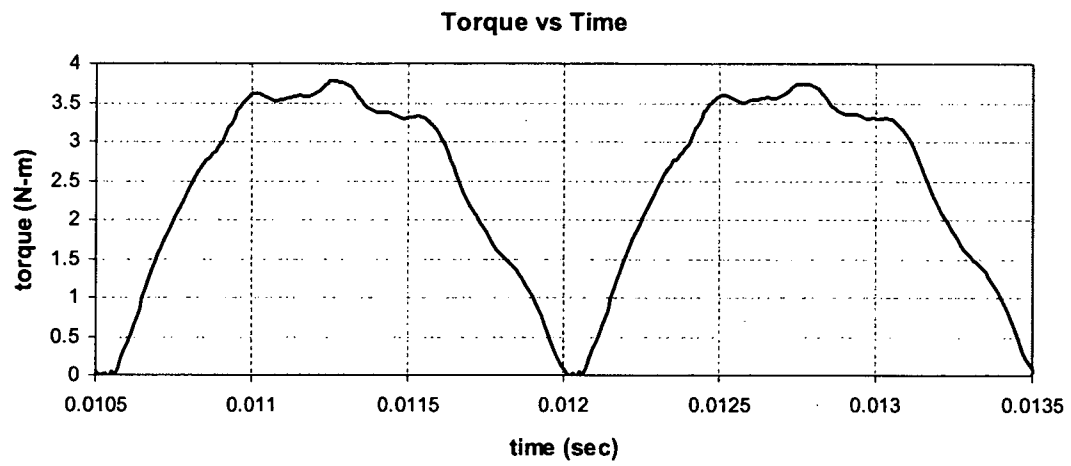


Fig. 10

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**Fig. 11**

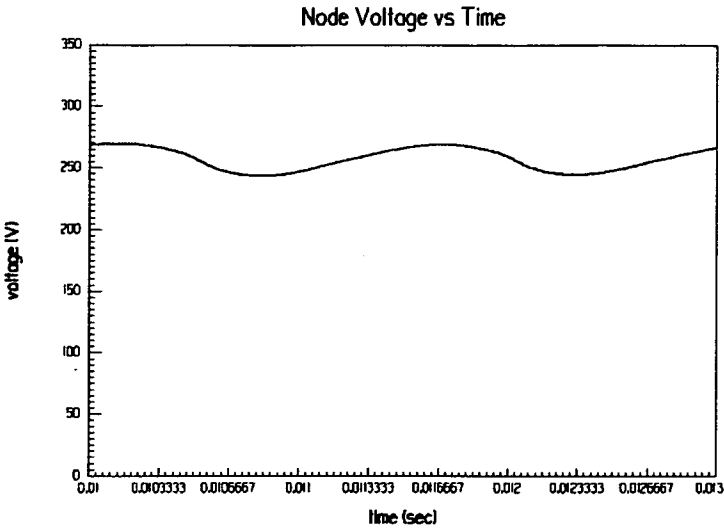
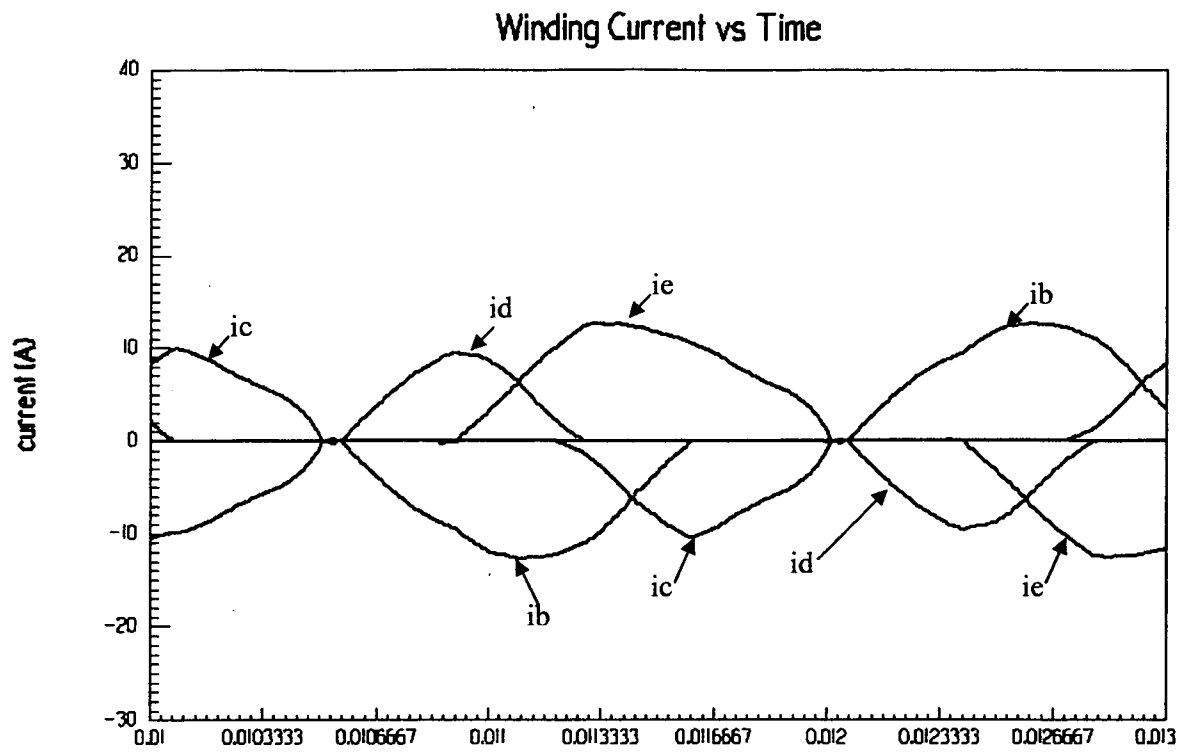


Fig.12

**Fig. 13**

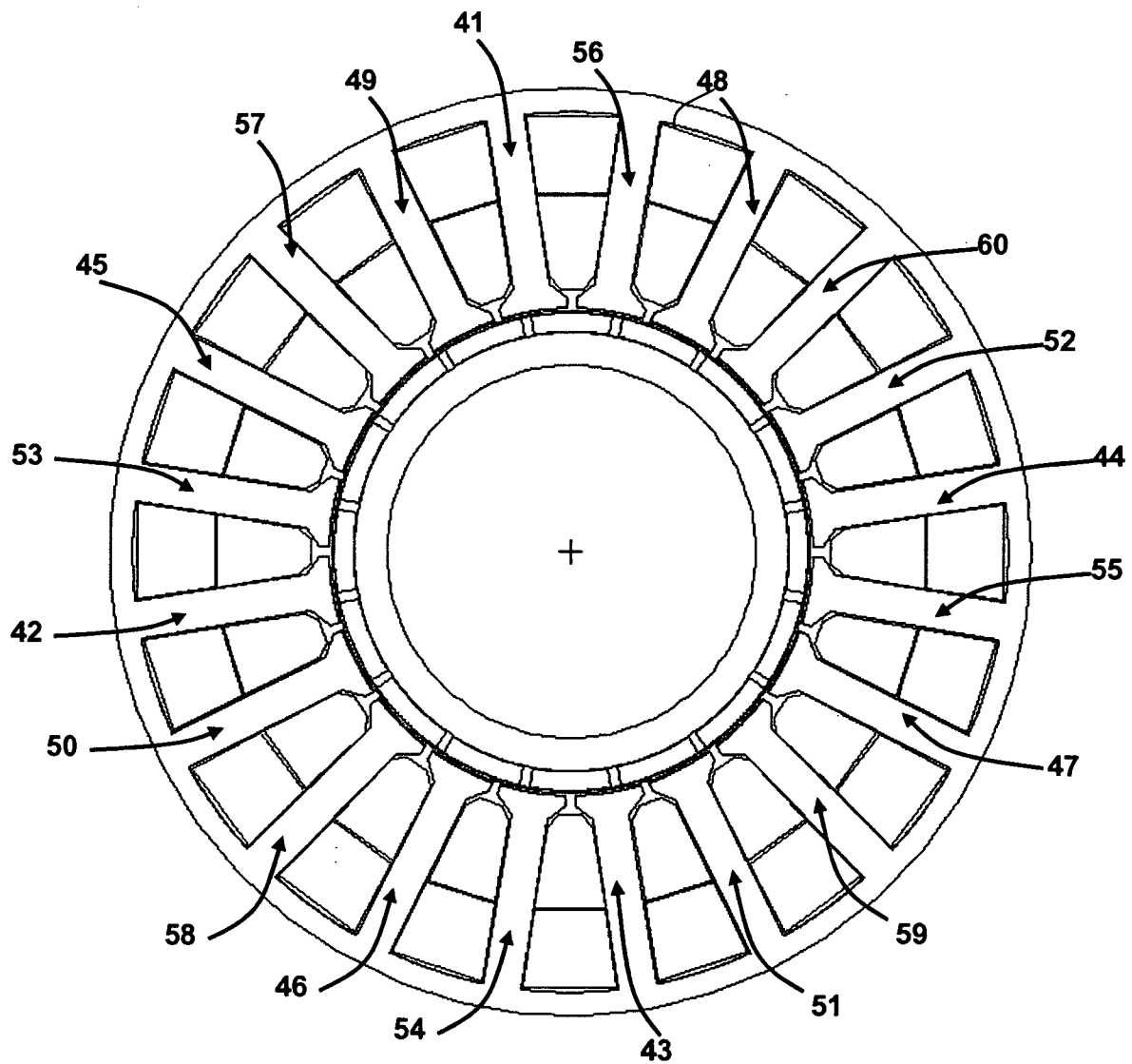


Fig. 14

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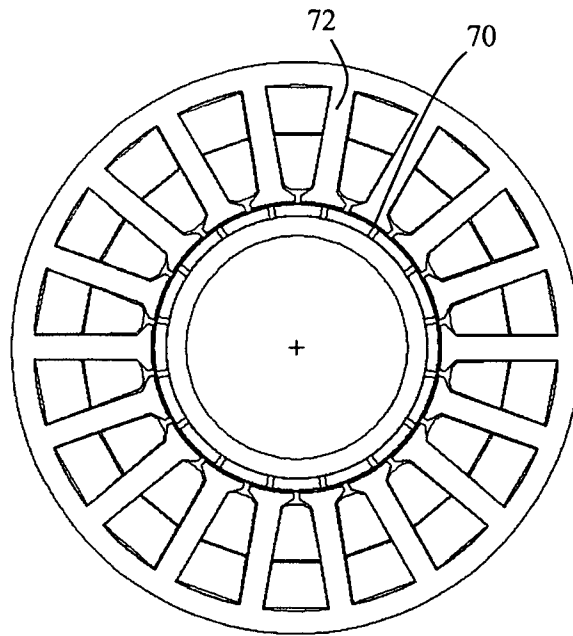
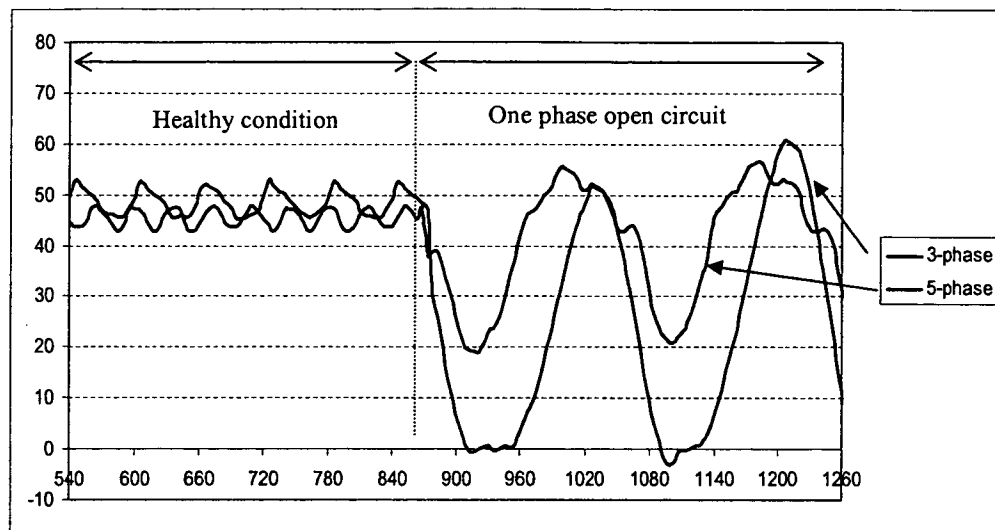


Fig. 15

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**Fig. 16**

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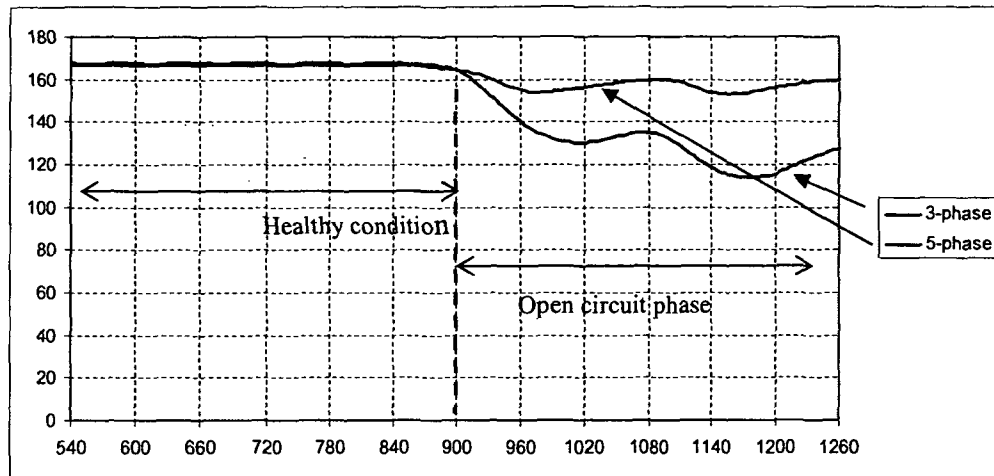


Fig. 17