(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 September 2006 (21.09.2006)

PCT

(10) International Publication Number
WO 2006/098703 A1

(51) International Patent Classification:
H02P 25/08 (2006.01) ***H02P 1/16*** (2006.01)

(21) International Application Number:
PCT/SI2006/000003

(22) International Filing Date:
15 February 2006 (15.02.2006)

(25) Filing Language: Slovenian

(26) Publication Language: English

(30) Priority Data:
P-200500045 21 February 2005 (21.02.2005) SI

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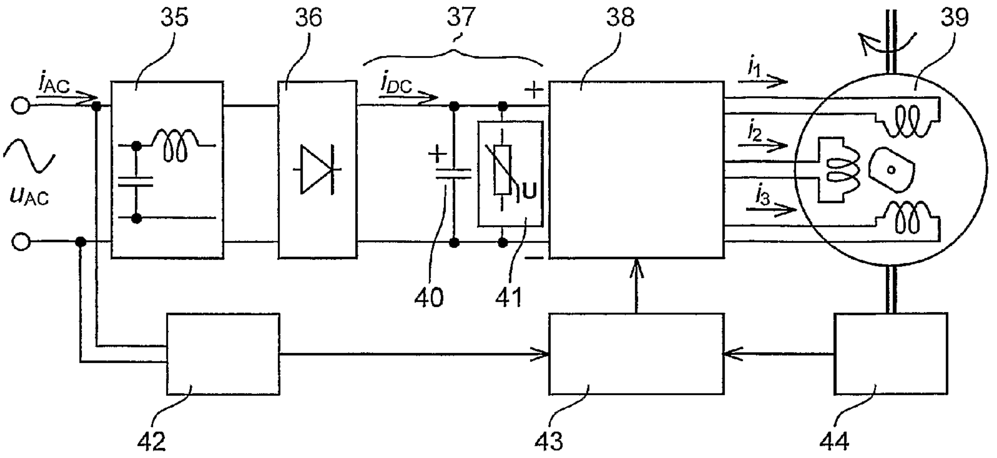
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: A CIRCUIT AND A METHOD FOR CONTROLLING A RELUCTANCE MOTOR



(57) Abstract: The invention relates to a circuit and a method for controlling a reluctance motor, powered from the public power transmission system (the power grid), and, in particular, it relates to a method of operation which allows the drive electronics to have fewer subsystems and consequently to be cheaper. The circuit according to the invention comprises a radiofrequency interference filter (35), a rectifier bridge (36), a voltage meter (42), an intermediate direct current circuit (37), a power output stage (38), a sensor (44) for measuring the rotational shift of the rotor or alternatively a sensorless algorithm, and a commutation logic (43). The circuit is made so that the voltage in -the intermediate direct current circuit (37) is pulsating, making the electric current (i_{AC}) drawn from the power grid compliant with the regulations on electromagnetic compatibility (EN61000-3-2). The electric currents (i_1, i_2, i_3) in the phase windings of the motor (39) must be limited in order for the power output stage (38) not to burn out. This is achieved by limiting the voltages in the phase windings of the motor (39), which is done by only switching the phase windings on when the voltage in the intermediate direct current circuit (37) viz. the power grid alternating voltage (u_{AC}) is sufficiently low in relation to the operating state of the motor (39).

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A Circuit and a Method for Controlling a Reluctance Motor

The invention relates to a circuit and a method for controlling a reluctance motor, powered from the public power transmission system (the power grid), and, in particular, it relates to a method of operation which allows the drive electronics to have fewer subsystems and consequently to be cheaper.

In household and other appliances, where there is a need for high rotating speeds or the rotating speed must be adjustable, drives with universal collector motors are employed. The universal collector motors are mainly used for their convenience. They consist of a stator with windings, a rotor with windings, and of brushes and a collector which commutate the current in the windings of the rotor. Due to the friction with the collector the brushes get worn out, causing such motors to have a short life span. Moreover, the brushes decay into dust that pollutes the environment. Also, the rubbing of the brushes against the collector gives rise to acoustic noise. In addition to this, sparkling takes place at the edge of the brushes, which is a source of radiofrequency interference.

Universal collector motors may be controlled by means of a simple and cheap electronic circuit, illustrated in Figure 1. The universal collector motor 2 is connected in series with a triac 3, triggered by the triggering circuit 4. As part of the electronic circuit there is also a filter for radiofrequency interference 1. The universal collector motor is controlled by means of the aperture angle α. During the aperture angle α, before the power grid voltage u_{AC} passes through zero, the triggering circuit 4 opens the triac 3. At that moment the current from the power grid i_{AC} starts to flow and keeps on flowing until the end of the half period of the power grid voltage u_{AC}. The triac 3 closes when the current passing through the said triac and consequently through the universal collector motor 2 drops to zero. The procedure is repeated every half period of the power grid voltage u_{AC}. The time diagrams 5 show the case in which the aperture angle α is small, determining, in turn, a small power and speed of the universal collector motor 2. As we increase the aperture angle α, the power and speed of the universal collector motor 2 increase accordingly. The time diagrams 6 show the case in which the aperture angle α is large. The highest power and speed are achieved when the aperture angle α is equal to the half period of the power grid voltage u_{AC}.

From a technical point of view, a brushless drive with a brushless permanent magnet motor or a brushless drive with a reluctance motor might be used instead of a drive with a universal collector motor. In the said two types of motors, instead of the brushes and the collector, the current passing through the windings is commutated by the electronics which are an integral part of the brushless drive and are complex and consequently expensive. The elevated price as compared to drives with a universal collector motor curtails the use of the brushless drives in high volume consumer appliances. On the other side, the brushless drive exhibits no technical limitations that are present in drives with universal collector motors and arise from the use of brushes and collectors.

A lower price would open the possibilities for employing brushless drives in high volume consumer appliances. The price of the drive may be cut down by reducing the number of electronic components utilized, which is to say the number of components of the electronic circuitry.

Known and used grid-driven brushless drives comprise subsystems shown in Figure 2. The motor 12 may be a brushless permanent magnet motor having any number of phases, or a reluctance motor having any number of phases. The phase windings of the motor 12 are connected to the power output stage 11, composed of semiconductor switches which commutate the electric current in the phase windings of the motor 12. This rectifying of the current must take place in accordance with the rotational offset of the rotor of the motor 12, as measured by the sensor 15. In cheaper drives, the said sensor 15 is generally made of Hall sensors. More expensive embodiments of the said sensor 15 comprise optical position transducers. The recent developments in processor semiconductor circuits have made it possible for sensorless brushless drives to be constructed wherein the motor 12 comprises no sensor 15 on the shaft. In this case, the motor 12 is mechanically simpler. The required information on the actual rotational offset of the shaft of the motor 12 in sensorless brushless drives is obtained from the measured electrical quantities and the recalculation thereof in processor semiconductor circuits. The information about the actual rotational offset of the shaft is required by the commutation logic 14 which opens the semiconductor switches in the power output stage 11.

The power output stage 11 gets the electric power from the intermediate direct current circuit 10. To prevent excessive oscillation of the voltage in the intermediate direct current circuit 10, a smoothing capacitor 13 is used to store electric energy. The smoothing capacitor 13 is an electrolytic capacitor. Its capacity depends upon the power of the drive and generally ranges from 100 µF to several 1000 µF. Since the smoothing capacitor 13 is large, it constitutes a considerable part of the overall electronics.

Before the smoothing capacitor 13 there is a power factor corrector 9 which shapes the electric current from the power grid i_{AC}. If the electronics did not comprise a power factor corrector 9, the smoothing capacitor 13 would only get filled in the proximity of the peak of the power grid voltage u_{AC}, and the amplitude of the filling current and consequently of the power grid current i_{AC} would be very big, as shown in the time diagrams 20 in Figure 4. The rest of the time the power grid current i_{AC} would be zero. Given that thus shaped power grid current i_{AC} heavily pollutes the public power grid, the electromagnetic compatibility standards EN61000-3-2 limit the content of higher harmonic components in the electric current drawn by appliances from the public power grid. By means of the power factor corrector 9, the smoothing capacitor 13 is filled in such a way that the current from the power grid i_{AC} contains fewer higher harmonic components and/or that said higher harmonic components are low enough to comply with the standard EN61000-3-2.

The power factor corrector 9 may be embodied as a passive filter or as a switching converter. The passive filter requires a large choke coil, the reactance of which greatly reduces the voltage in the intermediate direct current circuit 10. Being large, the choke coil is also heavy and expensive. Because of the reduced voltage and its weight and price, this embodiment of the power factor corrector 9 is less convenient for use in high volume consumer appliances. The power factor corrector 9 with a switching converter is composed of a choke coil, a semiconductor switch, a semiconductor diode, and the controller circuitry which switches on the semiconductor switch. In this embodiment, the choke coil is smaller as compared to the passive filter embodiment, making the whole circuit lighter. In spite of that, the switching converter with all the required elements is still large and costly.

At the electronics entry of a brushless drive there are a rectifier bridge 8 and a radio frequency interference filter 7. The rectifier bridge 8 rectifies the power grid alternating voltage u_{AC}. In the large majority of cases, a Greatz bridge is employed in the rectifier bridge 8. The radio frequency interference filter 7 filters out the interferences generated in the electronics by the fast switching on and switching off of the currents and voltages. The radio frequency interference filter 7 must be adequately dimensioned in order for the device to comply with the current electromagnetic compatibility standards (EN55014-1).

A large amount of effort is invested all over the world to reduce the number of components present in the entry stage of the electronics, viz. in the power factor corrector 9 and in the intermediate direct current circuit 10.

Figure 3 shows a circuit, composed of a Greatz bridge 16 and a load 17. The Greatz bridge 16 rectifies the power grid voltage u_{AC}, so that a pulsating load voltage u_L is obtained on the load 17. This voltage on the load u_L is followed by the current i_L that flows through the load and is likewise pulsating. After the current i_L is de-rectified, a power grid current i_{AC} is obtained having a shape that complies with the electromagnetic compatibility standards (EN61000-3-2). Such a circuit was employed by C. Larouci, J. P. Ferrieux, L. Gerbaud, J. Roudet, J. P. Keradec, in the paper *Optimisation of a PFC Flyback Converter in Discontinuous Conduction Mode*, Proceedings PCIM 2002, Nuremberg, May 2002, wherein a flyback switching converter is used in the place of the burden 17.

Usually a capacitor is connected in parallel with the switching converter in order to block the radio frequency interference caused by the switching converter. In Figure 4 the circuit of Figure 3 may be seen, with a capacitor 18 added in parallel to the load. As long as the capacitor 18 is kept small, it merely serves to block the radio frequency interference caused by the load, such as a switching converter. In this case, the electric quantities vary, as indicated in the time diagrams 19. The voltage on the load u_L is pulsating, each half period dropping to virtually zero. The rectified current i_{DC} is the sum of the current through the load i_L and the filling current of the capacitor 18. The current i_{DC} flows the greater part of the half period, so that when the current i_{DC} is de-rectified, the shape of the current from the power grid does not differ much from the sinus, which makes it compliant with the electromagnetic compatibility standards (EN61000-3-2). As the capacity of the capacitor 18 is increased, the voltage on the capacitor 18, which is to say the voltage on the load u_L, becomes smoother, as indicated in the time diagrams 20. The capacitor 18 is only filled during the peak of the power grid voltage u_{AC}. Consequently, the current i_{DC} flows in narrow pulses of great amplitude. The current drawn from the power grid i_{AC} by the circuit contains a lot of higher harmonic components, hence not complying with the electromagnetic compatibility standards (EN61000-3-2).

The permanent magnet brushless motor requires a comparatively stable voltage in the intermediate direct current circuit 10 to operate. The reason for this is the cutting voltage generated in the motor windings due to the rotation of the rotor. The amplitude of the cutting voltage is equal to the rotating speed multiplied by a constant. The voltage in the intermediate direct current circuit 10 must exceed the amplitude of the cutting voltage, so that the electric current generating the positive torque may flow into the motor 12. The electronics may ensure a stable voltage in the intermediate direct current circuit 10, provided that the smoothing capacitor 13 has a sufficient capacity. Owing to the smoothing capacitor 13 being so big, in turn, a power factor corrector 9 is required in order to ensure that a conveniently shaped electric current from the power grid i_{AC} flows into the electronics.

The stator 21 and the rotor 22 of the reluctance motor illustrated in Figure 5 are conveniently shaped so that the magnetic resistance to the magnetic flow, i. e. the inductance L of the phase winding 23, varies depending on the rotational shift ρ. The inductance L varies periodically with a period 25, and in the case of the motor shown in Figure 5, the said inductance L would have two periods.

The variation of inductance due to the rotational shift ρ in the phase winding 23, wherein the electric current i_F is flowing, generates the torque 24 on the shaft. This goes for each and all the phase windings in the reluctance motor. By conveniently commutating the electric current in the phase windings the resulting torque 24 will be positive. The voltage u_F applied to the phase winding 23 must be roughly equal to the sum of the voltage drop 26 on the resistance of the phase winding 23, the voltage drop 27 on the inductance L of the phase winding 23, and the voltage drop 28 caused by the power being generated on the shaft. Additional voltage drops occur in the phase winding 23 owing to the influence of other phase windings, however, said voltage drops being generally small, they are not included in the equation of Figure 5. If the electric current I_F is small, the voltage drop 28, which is a consequence of the power being generated on the shaft, is small even if the rotational speed of the motor is high. That is why the voltage in the intermediate direct current circuit of the electronics of the reluctance motor drive may be pulsating, as shown in the time diagrams 19, as opposed to the voltage in the intermediate direct current circuit 10 of prior-art electronics of the permanent-magnet brushless motor drive according to Figure 2, which voltage must be stable.

After explaining the time diagrams 19, it may be seen that the electronics for controlling the reluctance motor do not require a power factor corrector, provided that the voltage in the intermediate direct current circuit is pulsating.

Authors A. C. Clothier, S. Greetham, M. H. Haywood, N. J. Leighton, N. W. Philips in the Patent application *Power Conversion Apparatus*, GB 2396491 A, take advantage of the fact that the shape of the current flowing from the power grid i_{AC} into the electronics will be compliant with the electromagnetic compatibility standards (EN61000-3-2) as long as the electronics contain a capacitor of a sufficiently low capacitance in the intermediate circuit, as shown in the time diagrams 19 in Figure 4. The electronics mentioned in the said Patent application are powered from the power grid and supply power to the windings switched on and off by the said electronics. The winding may be a transformer, as in the case of the flyback switching converter mentioned above. Or alternatively, the windings may be the motor windings. In the Patent application GB 2396491 A, the authors do not describe how they carried out the start of the motor or how they regulate the speed and the power of the motor, but only describe the operation of the motor at its full power.

When the reluctance motor is rotating slowly, the voltage drop 28 caused by the power being generated on the shaft is small, even if the electric current i_F is big. If we were to apply a high voltage u_F to the phase winding 23 at a low rotational speed, the electric current i_F would reach very high levels. This occurs when the instantaneous value of the power grid alternating voltage u_{AC} is at its peak value. In that situation, the current i_F through the phase winding currently switched on would soar so high that it would blow the semiconductor switches in the power output stage and hence must be limited.

The current i_F may be limited by applying to the phase winding 23 a pulsating voltage u_F of a frequency that is generally above the audible range, that is to say a frequency of over 20 kHz, which is generated by the circuit shown in Figure 6. The said circuit is composed of a Greatz bridge 29, a capacitor 30 of small capacitance, and a half-bridge 34, comprising semiconductor switches V1 and V2 and diodes D1 and D2. The phase winding 23 may be switched on softly, causing the voltages and currents to be shaped as shown in Figure 7. If the phase winding 23 is switched on in a hard manner, the voltages and currents will be shaped as shown in Figure 8. The time axis in the diagrams of Figures 7 and 8 is given in the rotational shift ρ, for which the rotor 22 revolves at a given speed.

With the soft chopping as illustrated in Figure 7, semiconductor switches V_1 and V_2 are switched on at the moment t_1, so that the current i_F through the phase winding 23 is increasing. The said current i_F is flowing via the path 32 and is, at that particular moment, equal to the currents i_L and i_{DC} in Figure 6. Thereupon, the semiconductor switch V_1 is switched off, and the current i_F starts decreasing. At the moment t_2 the current i_F is being completed via the path 33 within the half-bridge 34. At the said time, the currents i_L and i_{DC} are equal to 0. However, such interruptions of the current i_{DC} and consequently of the current from the power grid i_{AC} produce huge radio frequency interferences.

With the hard chopping as illustrated in Figure 8, semiconductor switches V_1 and V_2 get switched on at the moment t_1, so that the current i_F through the phase winding 23 is increasing. The said current i_F is flowing via the path 32 and is, at that particular moment, equal to the currents i_L and i_{DC} in Figure 6. Thereupon, both the semiconductor switches V_1 and V_2 are switched off, and the current i_F starts decreasing. At the moment t_2 the current i_F is being completed via the path 31 and is filling the capacitor 30, so that the voltage at the said capacitor begins to increase. The current i_{DC} is equal to 0. When the semiconductor switches V_1 and V_2 are switched on again, the current flows via the path 32. At the moment t_3 the capacitor 30 is being emptied, which is why the current i_{DC} is still equal to 0. Just as in the case of the soft chopping, the interruptions of the current i_{DC} and consequently of the current from the power grid i_{AC} produce huge radio frequency interferences.

In prior-art circuits, wherein the capacitance of the smoothing capacitor 13 in the intermediate direct current circuit 10 is high, the said capacitance smoothes out the current peaks in the current i_L, so that these do not occur in the current i_{DC}.

An alternative approach for manufacturing a cheaper electronics was chosen by the authors L. Helle, G. K. Andersen, F. Blaabjerg, P. O. Rasmussen in their paper *An Integrated Single-Phase Power-Factor-Controlled Switched Reluctance Motor Drive*, Proceedings PCIM '99, Nuremberg, June 1999. The authors disclose a way of potentially lowering the cost of the drive by controlling the reluctance motor in such a manner as to require a lower-capacitance smoothing capacitor 13. The semiconductor switches in the power output stage 11 are controlled in such a way that the instantaneous power consumption in the motor is equal to the power supplied at that instant by the power factor corrector 9. The importance of the smoothing capacitor 13 for storing energy is thereby diminished, allowing it to have a very low capacitance. The cost of the drive is additionally reduced by winding the choke coil of the power factor corrector 9 onto the stator of the motor.

Prior-art circuits and methods for controlling a reluctance motor in grid-powered drives complying with the regulations on electromagnetic compatibility contain expensive components and are consequently not suitable for being built into comparatively cheap high volume consumer products, or else they generate radio frequency disturbances at certain points of operation, consequently requiring big filters to block radio frequency interference.

The object of the present invention is a circuit and a corresponding method for controlling a reluctance motor in a grid-powered drive, which will be compliant with the regulations on electromagnetic compatibility and will be composed of cheaper components, allowing it to be built into comparatively inexpensive high volume consumer products.

According to the present invention, the said object is achieved through a circuit and a method for controlling a reluctance motor as per the independent patent claims.

The circuit and the method for controlling a reluctance motor shall hereinafter be described with reference to the accompanying drawings, illustrating:
Figure 1: a prior-art circuit and method for controlling a universal collector motor;
Figure 2: a prior-art circuit for controlling brushless motors;
Figure 3: a prior-art rectifier circuit having no smoothing capacitor, and the operation thereof;
Figure 4: a prior-art rectifier circuit having a smoothing capacitor, and the operation thereof;
Figure 5: an embodiment of a prior-art three-phase reluctance motor;

Figure 6: the directions of the currents in the half-bridge of a prior-art pulsating feed of a motor phase winding;
Figure 7: a time diagram of the currents of a prior-art pulsating feed of a motor phase winding;
Figure 8: a time diagram of the currents of a prior-art pulsating feed of a motor phase winding;
Figure 9: the circuit for controlling the reluctance motor according to a first embodiment of the invention;
Figure 10: the circuit for controlling the reluctance motor according to a second embodiment of the invention;
Figure 11: the circuit for controlling the reluctance motor according to a third embodiment of the invention;
Figure 12: an embodiment of a power output stage for powering the reluctance motor according to the method of the invention;
Figure 13: the time diagram of the electric currents in the output stage according to the invention;
Figure 14: the time diagram of the electric currents and voltages when the motor is controlled according to the first method of the invention;
Figure 15: the time diagram of the electric currents and voltages when the motor is controlled according to the second method of the invention.

In the intermediate direct current circuit 37 situated between the rectifier bridge 36 and the power output stage 38 according to the invention and to Figures 9, 10 and 11, the electronics of the grid-powered drive with a reluctance motor comprise a capacitor 40 of a very small capacitance, so that in each half period the voltage at the said capacitor drops to 25 % of the maximum voltage reached thereat during the same half period, and also comprise a voltage-dependent circuit 41, or alternatively the electronics in the intermediate direct current circuit only comprise a voltage-dependent circuit and no capacitor 40. In the voltage-dependent circuit 41, the magnetic energy returning from the motor 39 is transformed into heat. In accordance with the invention and with Figures 9, 10 and 11, the grid-powered drive with a reluctance motor does not require a power factor corrector. In accordance with the invention and with the method of Figures 12 and 13, an electric current of a shape that causes fewer radiofrequency interferences flows into the power output stage 38. In accordance with the invention and with the method of Figures 14 and 15, the current flowing through the windings of the motor 39 is limited by switching on the phase currents of the motor 39 in synchronicity with the power grid alternating voltage u_{AC}.

Although the explanation of the invention is based on a three-phase reluctance motor, it is also valid for two-phase or multiphase reluctance motors.

Circuits for controlling a reluctance motor 39 with two or more phases according to the embodiments represented in Figures 9, 10 and 11 comprise a radiofrequency interference filter 35, a rectifier bridge 36, an intermediate direct current circuit 37 having a capacitor 40 and a voltage-dependent circuit 41 or alternatively having only a voltage-dependent circuit 41, a power output stage 38, a sensor 44, a commutation logic 43, and a voltage meter 42. The sensor 44 may be substituted by a sensorless algorithm.

The expression "voltage meter" 42 refers to an electronic circuit which yields information on the power grid voltage u_{AC} passing through the zero point.

The switching on and off of the currents and voltages in the power output stage 38 occurs in a very quick succession, giving rise to radiofrequency interference. It is therefore desirable that as few as possible such commutations take place. The fewest take place if they only occur when the current is commutated from a given phase winding 46 to the next phase winding 47, and subsequently to the phase winding 48. Thus, during one period of the inductance variation 25 resulting from rotation, each of the phase windings of the motor 39 gets switched on and off only once, exception being made for very low speeds and the starting of the motor when the duration of one period of the inductance variation 25 is longer than the half period of the power grid voltage u_{AC}. At such moments, due to the inventive method of regulating the power viz. the speed, the phase winding of the motor 39 might get switched on and off several times during a given period of the inductance variation 25, but still only once during any given half period of the power grid voltage u_{AC}.

Figure 12 depicts the circuit of the power output stage 38, to which the phase winding 46, the phase winding 47 and the phase winding 48 of the reluctance motor are connected. The circuit of the power output stage 38 consists of the diodes D_1 to D_6 and of the semiconductor switches V_1 to V_6, which may be bipolar transistors, MOSFETs, or IGBTs. The current i_1 flows through the phase winding 46, the current i_2 flows through the phase winding 47, and the current i_3 flows through the phase winding 48. The unfolding of the currents i_1, i_2 and i_3 is shown in the diagrams of Figure 13, wherein the events taking place within a single revolution are represented, the duration of such a single revolution being substantially shorter than the half period of the grid voltage u_{AC}.

At the moment t_1 in the time diagrams of Figure 13 the semiconductor switches V_1 and V_2 are switched on, so that the current i_1 passing through the phase winding 46 flows via the path 50. At the said moment the current i_L is equal to the current i_1.

The procedure of commutating the current from the phase winding 46 to the phase winding 47 starts with the semiconductor switches V_3 and V_4 i. e. the phase winding 47 switching on. The moment at which the phase winding 47 gets switched on varies depending on the speed of and the load on the motor 39. At the moment t_2 the current i_2 is increasing and flowing via the path 52. The current i_L is now the sum of the currents i_1 and i_2. The phase winding 46 is switched off by first switching off only the semiconductor switch V_1, so that at the moment t_3 the current i_1 is being completed via the path 51 through the semiconductor switch V_2 and the diode D_1 of the half-bridge 34 in the power output stage 38. During this time, the inductance of the phase winding 46 must still keep increasing, so that the current i_1 in the said phase winding 46 keeps generating torque and consequently keeps decreasing. Instead of switching off the semiconductor switch V_1, we could switch off the semiconductor switch V_2, thereby forcing the current i_1 to complete through the semiconductor switch V_1 and the diode D_2. The time during which the current i_1 is being completed within the half-bridge 34 may be longer than 5 % of the period of the inductance variation 25. When the current i_2 becomes bigger than the current i_1, we switch off the semiconductor switch V_2 as well. Then, at the moment t_4, the current i_1 is flowing from the half-bridge 34 via the path 49 and is subtracted from the current i_2 flowing via the path 52. Given that the current i_2 is bigger than the current i_1, the current i_L is greater than zero. When the current i_1 drops down to zero, the commutation of the current from the phase winding 46 to the phase winding 47 is finished.

When the motor 39 starts rotating forward, the commutation of the current from the phase winding 47 to the phase winding 48 begins, and so on as the motor rotates.

During the commutation the current i_L did not drop to zero, that is, it did not begin flowing backwards to the intermediate direct current circuit 37. There is accordingly no need of the capacitor 40 during operation. In the event that at the moment t_1 both the semiconductor switches V_1 and V_2 had to be switched off, the current i_L would start flowing in the reverse direction, that is to say, the energy would begin flowing back from the magnetic field inside the motor 39 to the intermediate direct current circuit 37. The said energy may be stored inside the capacitor 40, or converted into heat on the voltage-dependent element 41.

When starting the motor and to regulate the power, viz. the speed, the currents flowing through the windings of the motor 39 must be limited. This is achieved by lowering the voltage at the windings of the reluctance motor 39, which is done by switching on the phase windings of the motor 39 in synchronicity with the power grid voltage u_{AC}. When the motor is rotating very slowly, the phase windings of the motor 39 are only switched on in the proximity of the passage of the power grid voltage u_{AC} through point zero. As long as the rotation is slow, the aperture angle α as indicated in Figures 14 and 15 is small. For the duration of the aperture angle α, the electronics commutate the currents i_1, i_2 and i_3 in the phases of the motor 39, as required by the rotational shift of the rotor. As the speed of the motor 39 increases, the aperture angle α may be enlarged without resulting in an overly big current flowing through the phase windings of the motor 39. When the motor 39 reaches its nominal speed, the aperture angle α is equal to π. In that situation the power output stage 38 commutates the current in the phase windings of the motor 39 without any interruptions. In Figures 14 and 15, the duration of a single rotational shift 53 of the motor 39 is also indicated, valid in the case of the motor 39 being identical to the motor in Figure 5.

The regulation of the power viz. of the speed of the reluctance motor 39 during the start and the operation with the aperture angle α may be accomplished in two different ways. The first way is to make the electronics switch on and off the phase windings of the motor 39 in such a way that the electric currents i_1, i_2, i_3 in the phases of the motor 39 start to flow at the instant of angle β in the proximity of the passage of the power grid voltage u_{AC} through 0 and then continue flowing only during the aperture angle α, as indicated in Figure 14. The second way is to make the electric currents i_1, i_2, i_3 in the phases of the motor 39 flow only during the aperture angle α, and stop flowing at the instant of angle β in the proximity of the passage of the power grid voltage u_{AC} through zero, as indicated in Figure 15. This second way is analog to the method of controlling a universal collector motor 2 with a triac 3, as represented in Figure 1. In both the above said ways the duration of the aperture angle α may assume values from zero to half of the period of the power grid voltage u_{AC}.

The angle β designates the amount by which the electric currents i_1, i_2, i_3 in the phases of the motor 39 precede or follow the moment of passage of the power grid voltage u_{AC} through zero. When the electric currents i_1, i_2, i_3 start or stop flowing, the angle β is temporally offset from the passage of the power grid voltage u_{AC} through zero by less than 20 % of the half period of the power grid voltage u_{AC}.

According to a first embodiment of the circuit, illustrated in Figure 9, the information on the actual value of the power grid voltage u_{AC} viz. the moment of passage of the power grid voltage u_{AC} through zero is forwarded to the commutation logic 43 by the voltage meter 42. Consequently, the commutation logic 43 can control the aperture angle α in synchronicity with the power grid voltage u_{AC}. In addition, the commutation logic 43 can take care of the commutation of the currents i_1, i_2, i_3 in dependence of the rotational shift of the rotor of the motor 39. To operate, the commutation logic 43 also requires the information on the desired speed viz. the desired torque.

According to a second embodiment of the circuit, illustrated in Figure 10, the current flowing through the phase windings of the motor 39 is interrupted in synchronicity with the power grid, thus controlling the aperture angle α with the additional semiconductor switch 45 in the intermediate direct current circuit 37, to which the information on the actual value of the power grid voltage u_{AC} viz. on the moment of passage of the power grid voltage u_{AC} through zero is forwarded. The semiconductor switch 45 may be placed in the positive or in the negative branch of the intermediate direct current circuit 37.

According to a third embodiment of the circuit, illustrated in Figure 11, the current flowing through the phase windings of the motor 39 is interrupted in synchronicity with the power grid, thus controlling the aperture angle α already in the rectifier bridge 36, which is equipped with controlled semiconductor switches. In this case, the information on the actual value of the power grid voltage u_{AC} viz. on the moment of passage of the power grid voltage u_{AC} through zero is forwarded to the rectifier bridge 36.

In the latter two embodiments, the power output stage 38 merely directs the current to the appropriate winding of the motor 39, depending on the rotational shift of the rotor.

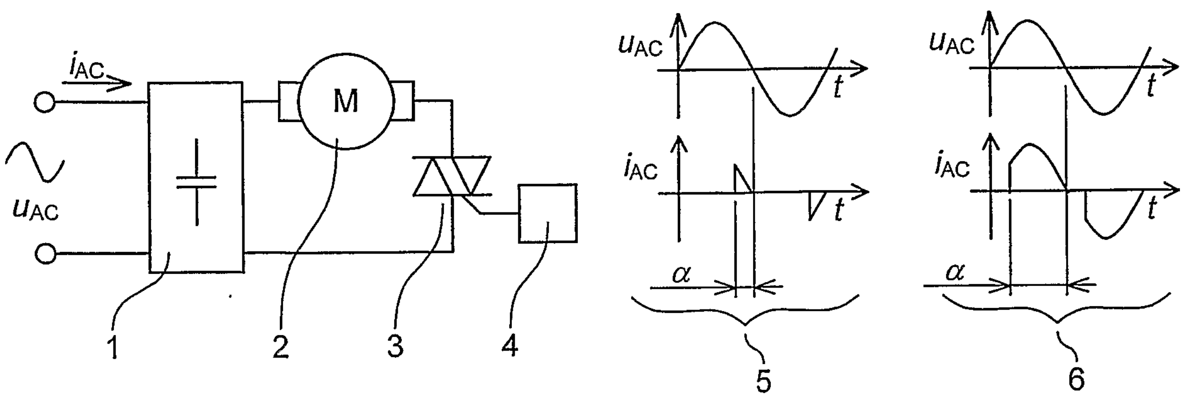
Patent Claims

1. A method for controlling the power viz. the speed of a reluctance motor (39) during the start and the operation thereof, characterized in that the electronics switch the phase windings of the motor (39) on and off in such a way that the electric currents in the phases of the motor (39) start flowing at the instant of angle (β) in the proximity of the passage of the power grid voltage (u_{AC}) through zero, and then continue to flow only for the duration of the aperture angle (α).
2. A method for controlling the power viz. the speed of a reluctance motor (39) during the start and the operation thereof, characterized in that the electronics switch the phase windings of the motor (39) on and off in such a way that the electric currents in the phases of the motor (39) only flow for the duration of the aperture angle (α), and stop flowing at the instant of angle (β) in the proximity of the passage of the power grid voltage (u_{AC}) through zero.
3. A method according to Claims 1 and 2, characterized in that the duration of the aperture angle (α) may assume values from zero to half of the period of the power grid voltage (u_{AC}).
4. A method according to Claims 1 and 2, characterized in that the angle (β) is temporally offset from the passage of the power grid voltage (u_{AC}) by less than 20 % of the half period of the power grid voltage (u_{AC}).

5. A method according to Claims 1 and 2, characterized in that each of the phase windings of the motor (39) gets switched on and off only once during any given time that is shorter than one period of the inductance variation (25) due to rotation and also shorter than a half period of the power grid voltage (u_{AC}).
6. A method according to Claims 1 and 2, characterized in that, after the phase winding is switched off, the electric current is first being completed within the half-bridge (34) in the power output stage (38) for a time that is longer than 5 % of the period of the inductance variation (25), whereupon the electric current of the switched-off phase flows from the half-bridge (34).
7. A method according to Claims 1, 2, 5 and 6, characterized in that the commutation logic (43) in synchronicity with the power grid voltage (u_{AC}) controls the aperture angle (α).
8. A method according to Claims 1, 2, 5 and 6, characterized in that the semiconductor switch (45) in the intermediate direct current circuit (37) in synchronicity with the power grid voltage (u_{AC}) controls the aperture angle (α).
9. A method according to Claims 1, 2, 5 and 6, characterized in that the rectifier bridge (36), comprising controlled semiconductor switches, in synchronicity with the power grid voltage (u_{AC}) controls the aperture angle (α).
10. A method according to Claims 7 to 9, characterized in that the synchronization of the control of the

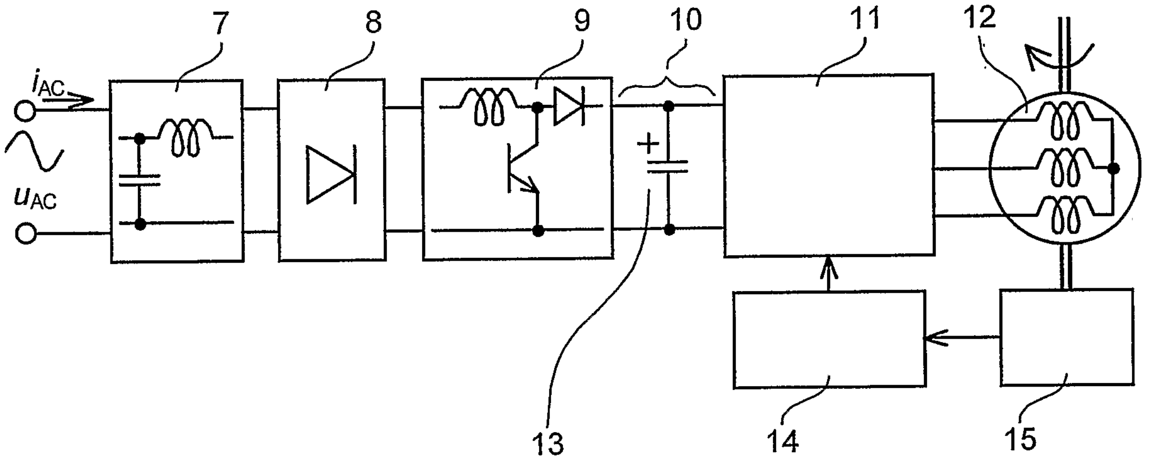
aperture angle (α) is accomplished by means of a voltage meter (42).

11. A circuit for implementing the method of Claims 1 to 10 by means of electronics for controlling a reluctance motor, said electronics consisting of a rectifier bridge (36), an intermediate direct current circuit (37) and a power output stage (38), characterized in that the said intermediate direct current circuit comprises a capacitor (40) and a voltage-dependent circuit (41).
12. A circuit for implementing the method of Claims 1 to 10 by means of electronics for controlling a reluctance motor, said electronics consisting of a rectifier bridge (36), an intermediate direct current circuit (37) and a power output stage (38), characterized in that the said intermediate direct current circuit only comprises a voltage-dependent circuit (41) and no capacitor (40).
13. A circuit according to Claim 12, characterized in that in the voltage-dependent circuit (41) the magnetic energy returning from the motor (39) is transformed into heat.



i_{AC}
u_{AC}
M
1
2
3
4
u_{AC}
t
i_{AC}
t
α
5
u_{AC}
t
i_{AC}
t
α
6

FIG. 1



i_{AC}
u_{AC}
7
8
9
10
11
12
+
13
14
15

FIG. 2

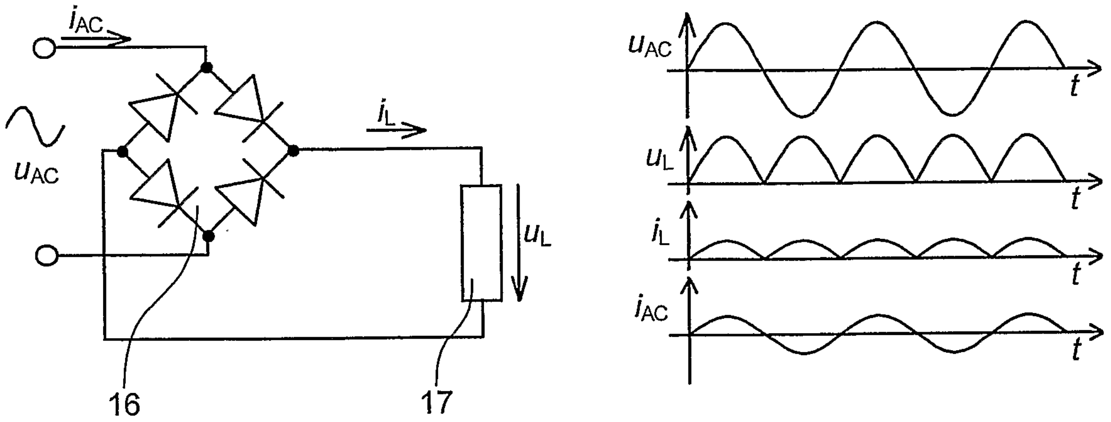

i_{AC}
u_{AC}
i_L
u_L
16
17
u_{AC}
t
u_L
t
i_L
t
i_{AC}
t

FIG. 3

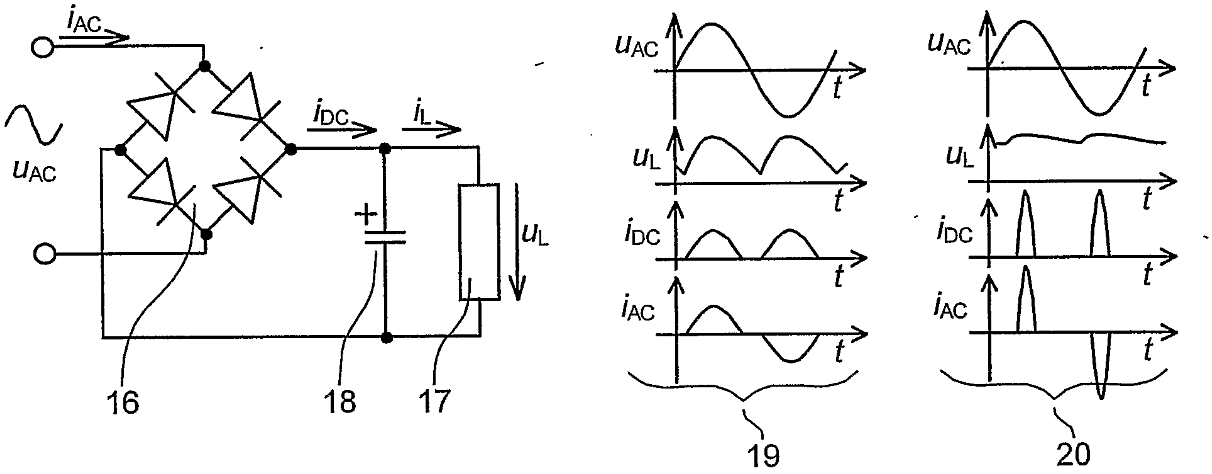
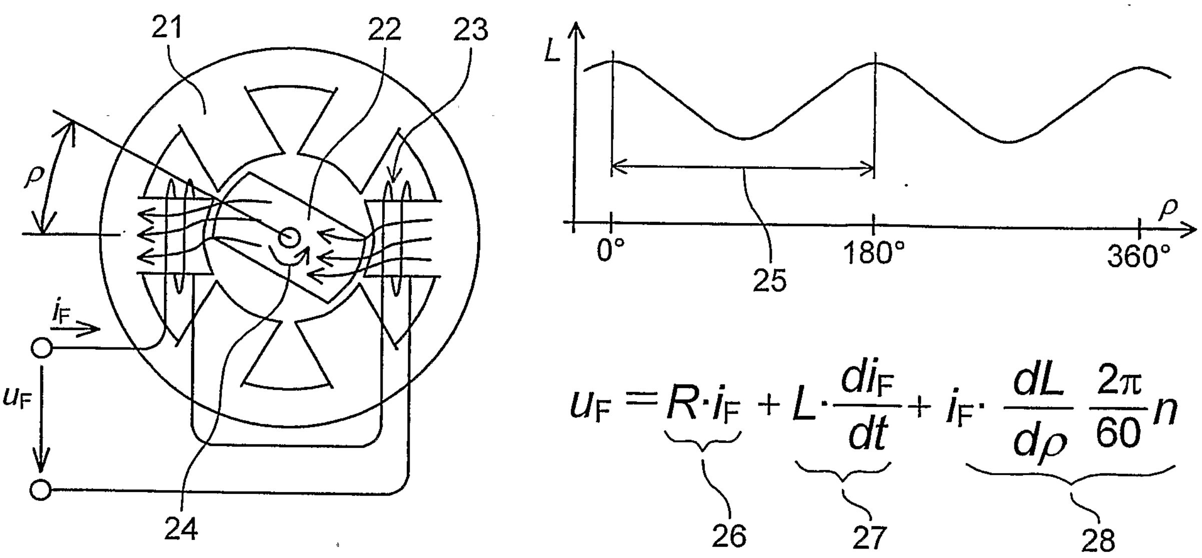

i_{AC}
u_{AC}
i_{DC}
i_L
+
u_L
16
18
17
u_{AC}
t
u_L
t
i_{DC}
t
i_{AC}
t
19
u_{AC}
t
u_L
t
i_{DC}
t
i_{AC}
t
20

FIG. 4



$$u_F = \underbrace{R\cdot i_F}_{26} + \underbrace{L\cdot\frac{di_F}{dt}}_{27} + \underbrace{i_F\cdot\frac{dL}{d\rho}\,\frac{2\pi}{60}n}_{28}$$

FIG. 5

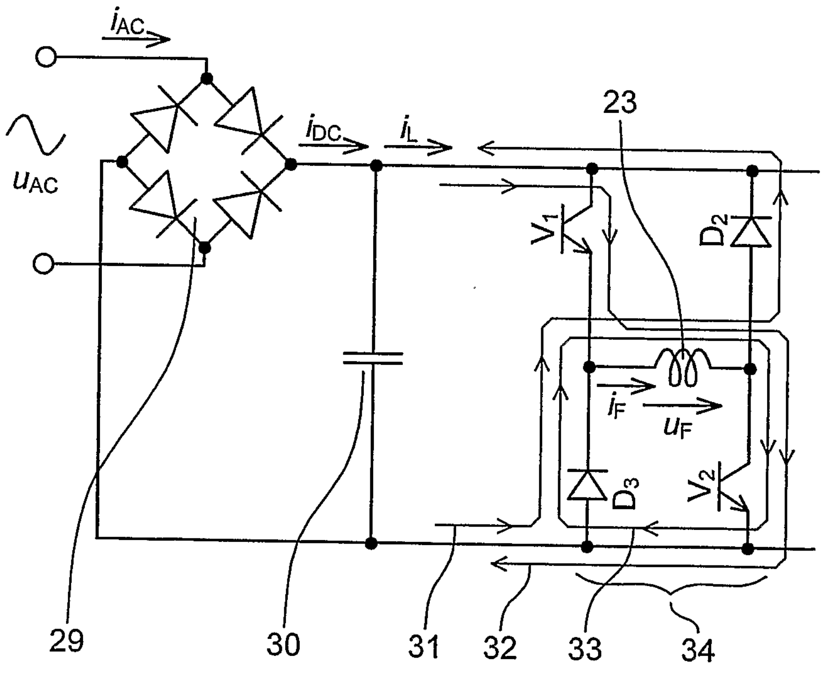


FIG. 6

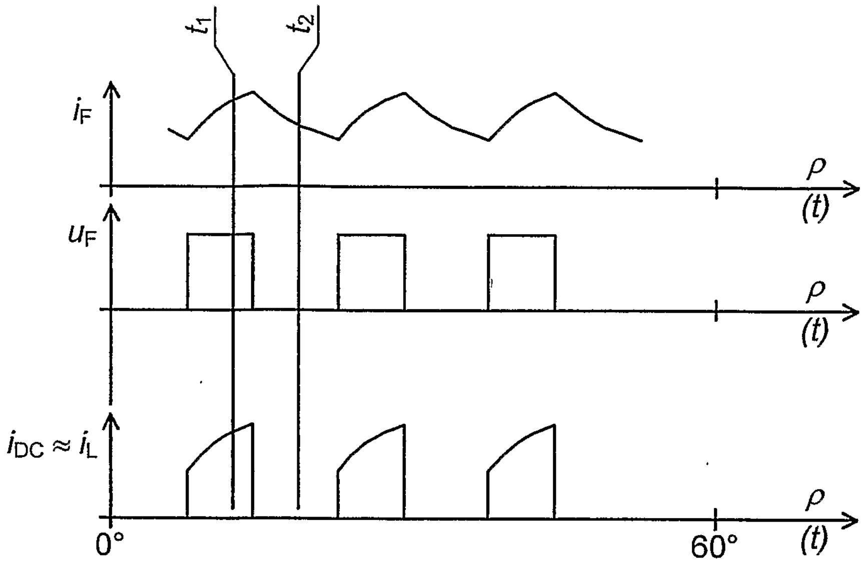


FIG. 7

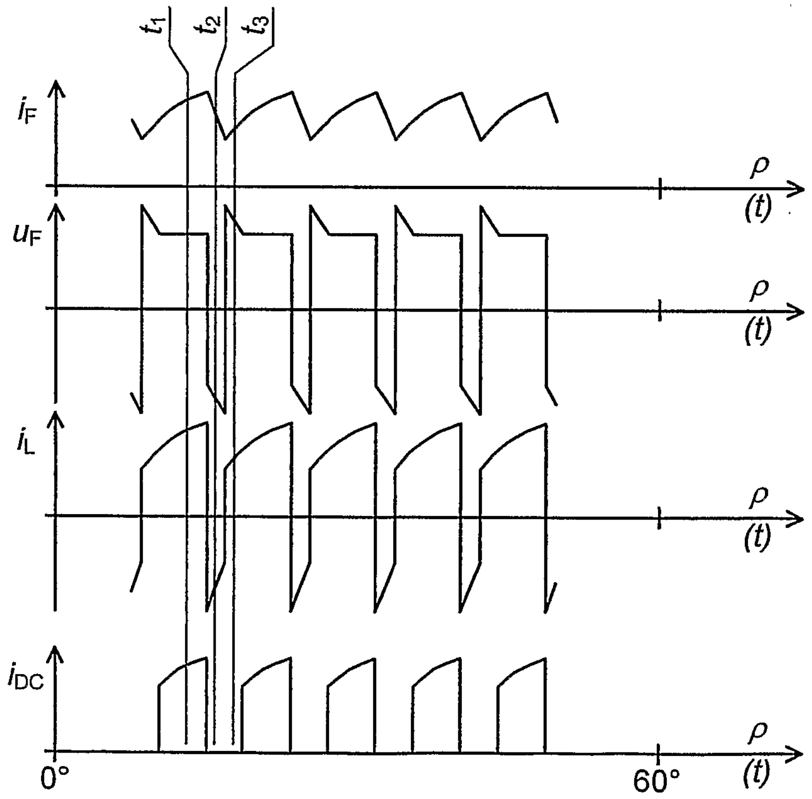


FIG. 8

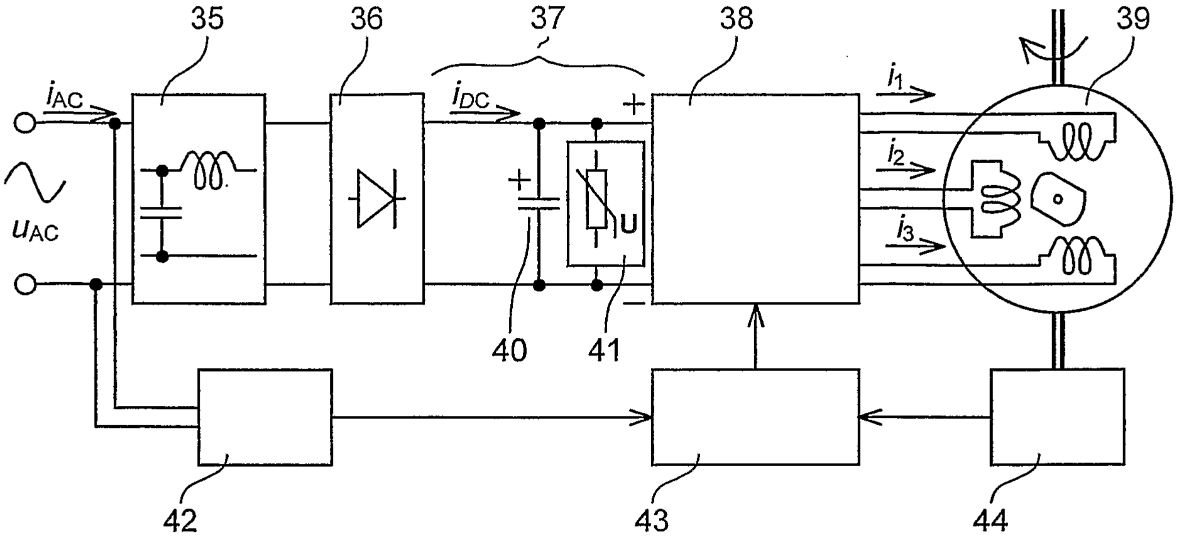

35
36
37
38
39
i_{AC}
i_{DC}
u_{AC}
i_1
i_2
i_3
+
−
U
40
41
42
43
44

Fig. 9

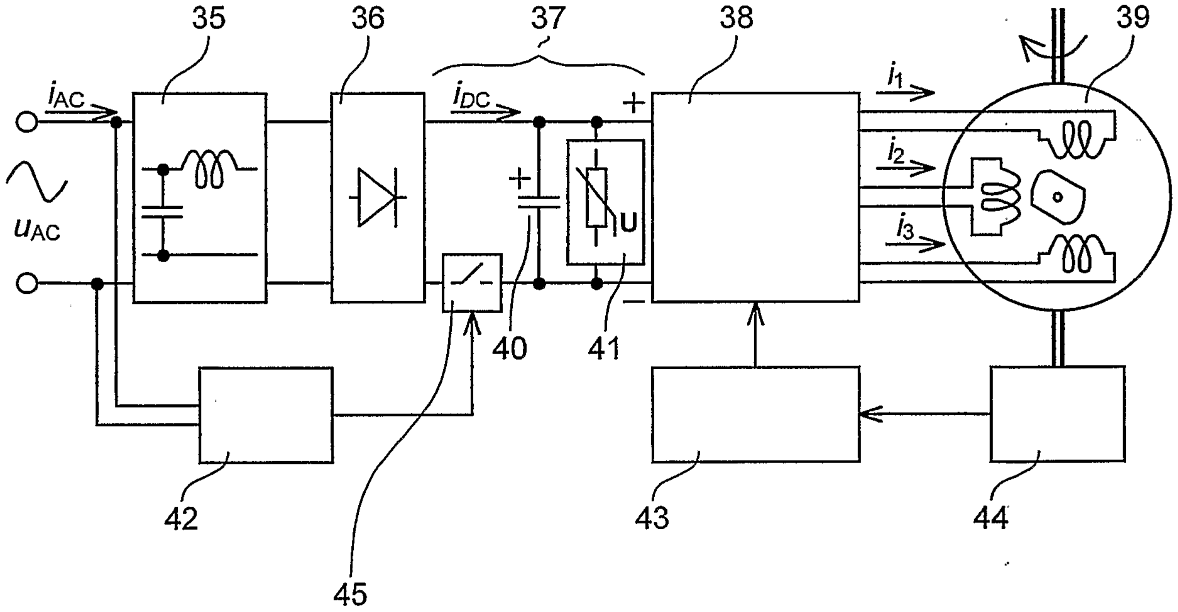

35
36
37
38
39
i_{AC}
i_{DC}
u_{AC}
i_1
i_2
i_3
+
−
U
40
41
42
43
44
45

Fig. 10

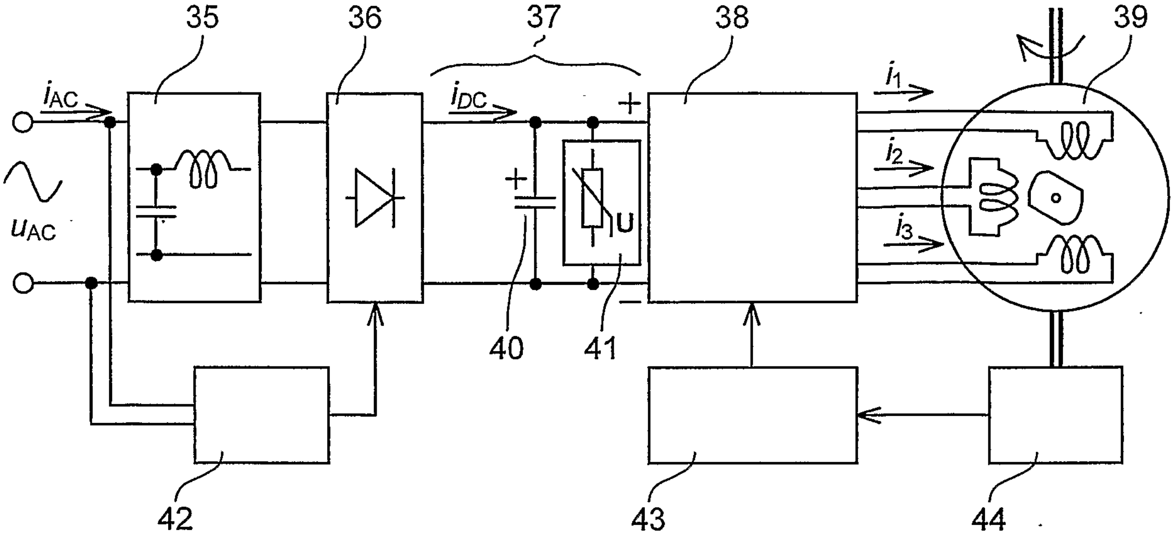

35
36
37
38
39
i_{AC}
u_{AC}
i_{DC}
+
−
U
i_1
i_2
i_3
40
41
42
43
44

FIG. 11

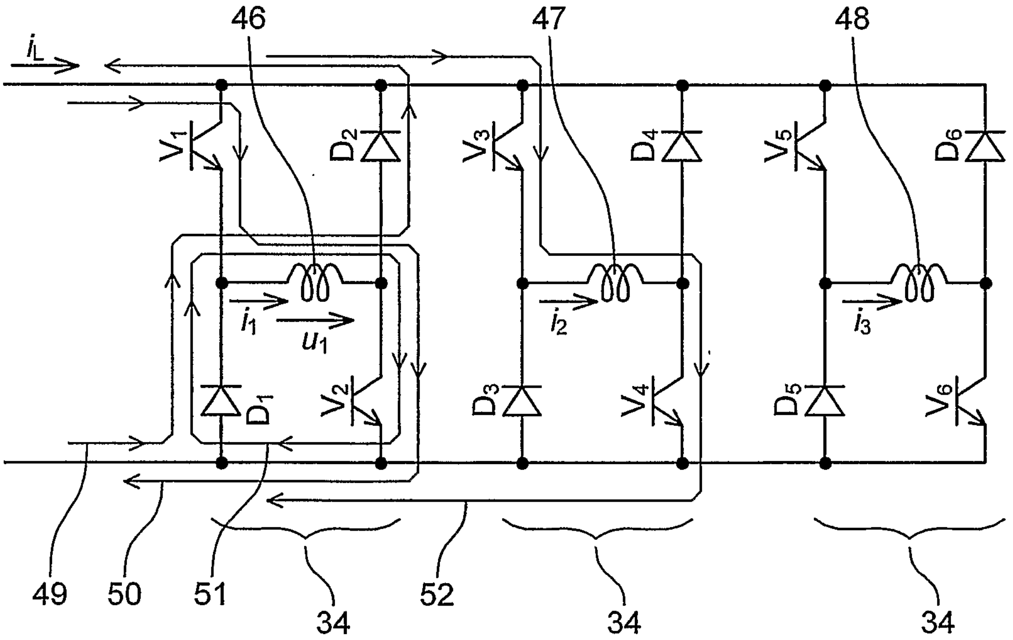

46
47
48
i_L
V_1
D_2
V_3
D_4
V_5
D_6
i_1
u_1
i_2
i_3
D_1
V_2
D_3
V_4
D_5
V_6
49
50
51
52
34
34
34

FIG. 12

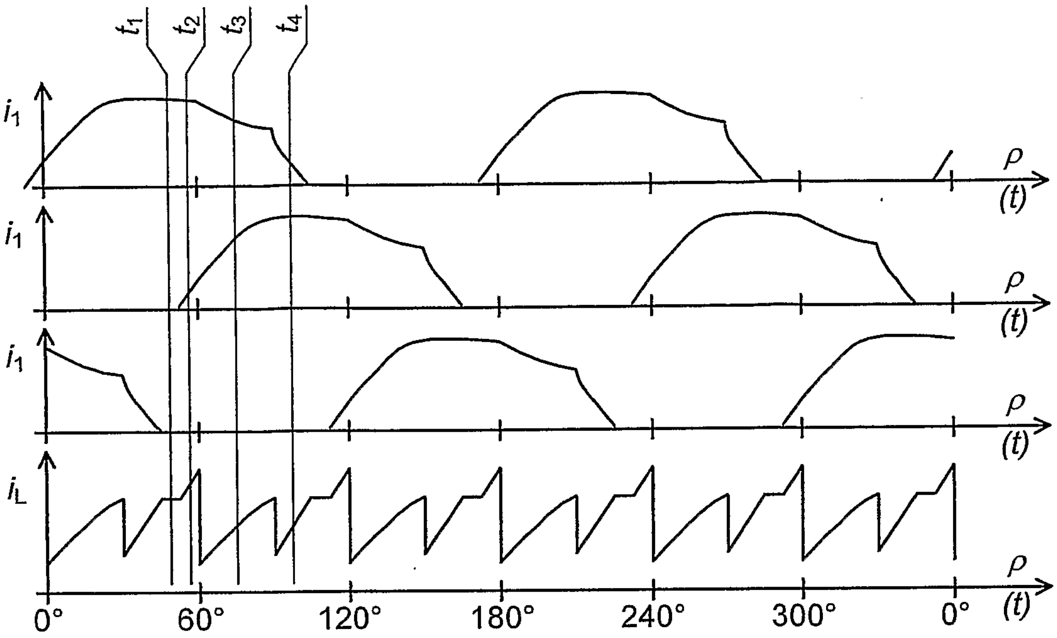


FIG.13

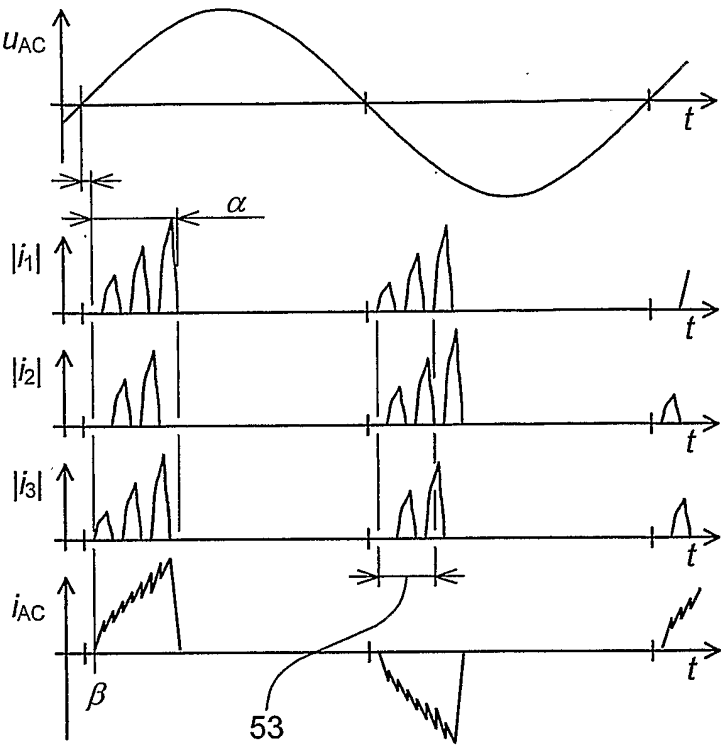


FIG. 14

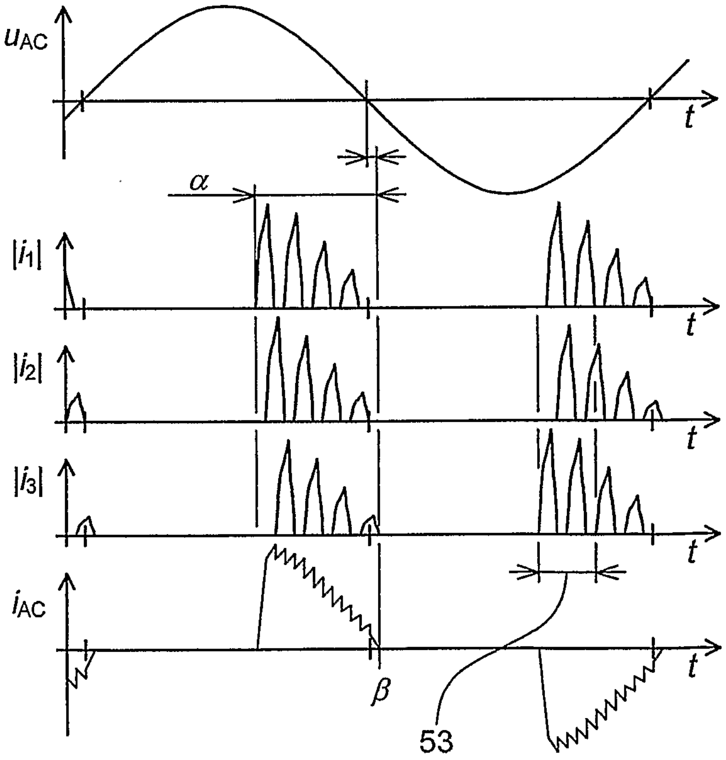


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/SI2006/000003

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02P25/08 H02P1/16

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)
H02P

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 practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 208 113 B1 (LELKES ANDRÁS ET AL) 27 March 2001 (2001-03-27)	1-10
Y	abstract column 2, lines 23-28 column 5, lines 18-43 figures 5,6	11-13
Y	PATENT ABSTRACTS OF JAPAN vol. 1996, no. 03, 29 March 1996 (1996-03-29) & JP 07 312826 A (SHIBAURA ENG WORKS CO LTD), 28 November 1995 (1995-11-28) abstract	11-13
	-/--	

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search 6 June 2006	Date of mailing of the international search report 21/06/2006
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Roider, A

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 299 18 256 U1 (ROBERT BOSCH GMBH) 1 March 2001 (2001-03-01) page 3, paragraph 3 claim 5 figure 1	11-13
A	ANDERSEN G K ET AL: "AN INTEGRATED SINGLE PHASE POWER FACTOR CONTROLLED SWITCHED RELUCTANCE MOTOR DRIVE WITH MINIMUM OF PASSIVE COMPONENTS" 8TH EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS. LAUSANNE, CH, SEPT. 7 - 9, 1999, EPE . EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS, BRUSSLS : EPE ASSOCIATION, BE, vol. CONF. 8, 7 September 1999 (1999-09-07), pages 1-9, XP000890323 ISBN: 90-75815-04-2 cited in the application abstract figures 1,2	1-13
A	GB 2 396 491 A (* DYSON LIMITED; * DYSON TECHNOLOGY LIMITED) 23 June 2004 (2004-06-23) cited in the application abstract figure 1	1-13

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/SI2006/000003

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			WO	2004057747 A1	08-07-2004
			JP	2006511186 T	30-03-2006