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(54) PROTECTION OF ELECTRICAL INVERTERS

(71) We, DANFOSS A/S, a Danish Company, of DK-6430 Nordberg, Denmark, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the protection of electrical inverters.

A known form of inverter has a series switching regulator connected to a smoothing capacitor and controllable by a signal of variable pulse width and/or frequency to feed a regulated D.C. voltage to semiconductor switching elements selectively switchable to derive an A.C. voltage from the regulated D.C. voltage. It is also known to monitor a parameter of the circuit by means of a sensor and a comparator and to feed an error signal from the comparator to a signal generator for the regulator when the parameter lies outside a permitted range.

Inverters with excess current protective circuits are known. It is known to connect a current measuring resistor in one of the D.C. connecting lines between the series regulator and the filter capacitor. If the voltage across this measuring resistor exceeds a limiting value set at a comparator, the voltage in the intermediate smoothing circuit is reduced by means of the series regulator to such an extent that a predetermined maximum current is not exceeded.

Even when this maximum current was still completely within the permissible rating of the semi-conductor switching elements of the inverter, it was found that these semiconductor switching elements were sometimes destroyed. This is particularly so if power transistors are used instead of controlled rectifiers as the switching elements.

It is an object of the invention to provide an inverter circuit which has a high degree of protection against destruction of the semi-conductor switching elements, particularly transistors.

According to the invention there is provided an inverter circuit comprising:

a series switching regulator connected to a smoothing capacitor and controllable by a signal of variable pulse width and/or frequency to feed a regulated DC voltage to semi-conductor switching elements selectively switchable to derive an AC voltage from the regulated DC voltage,

a regulator signal generator to provide a signal of variable pulse width and/or frequency to control the regulator,

an inverter signal generator to provide switching signals for the semi-conductor switching elements,

a current sensor connected in series with an inductor in a DC supply lead between the smoothing capacitor and the semiconductor switching elements, the current sensor and inductor being bridged by means to conduct in the opposite direction to the normal direction of current flow through the sensor, and

a disabling circuit operative on detection, by a parameter monitoring circuit including the current sensor, of current sensed by the current sensor exceeding a predetermined value to prevent the inverter signal generator from switching on said semi-conductor switching elements whilst the predetermined value is exceeded and the regulator signal generator from switching on the regulator for a predetermined period to allow the smoothing capacitor to discharge.

The circuit is based on the fact that burning out of the semi-conductor switching elements finds its cause in the discharge current of the smoothing capacitor, this current flowing until the capacitor voltage has adapted to the new voltage that is to obtain by reason of the detected excess current. Since excess currents are often caused by short-circuits and transistors cannot withstand such short circuit currents until the voltage has been reduced, when an excess current is detected the semi-conductor switching elements are completely switched off. In addition, the voltage supply is substantially interrupted by way of the series regulator. The inducor, however, attempts to maintain that current flowing through itself at the time of initiation of disablement and sends current through the means to conduct oppositely to the normal direction. After a certain time the current has dropped sufficiently for the disabling circuit to again allow the semi-conductor switching to become conductive in sequence and the smoothing capacitor starts to discharge through the load circuit. By reason of the inductance present, the discharge current rises slowly but as soon as it exceeds the predetermined value the parameter monitoring circuit responds and the disabling circuit again prevents the semi-conductor switching elements from being switched on. The discharge current dies away, the disabling circuit allows the semi-conductor switching elements to conduct and a new discharge cycle commences. In this way the smoothing capacitor is discharged in steps without the use of additional switching elements. With the aid of the inductor one can ensure a definite rise of the discharge current, and, with due consideration to the means to conduct oppositely to the normal direction, also a definite drop in the discharge current. In this way the operative and inoperative periods of the semi-conductor switching elements can be adapted to the permissible load limits. The duration of the predetermined period can be readily selected to be so long that the capacitor is fully discharged before the voltage supply is re-applied. When normal operation is re-established after the end of the predetermined period, the voltage is sufficiently low to prevent damage to the semi-conductor switching elements. If the current rises again because the short circuit has not been eliminated, the disabling circuit operates again so that no or hardly any load is applied to the semi-conductor switching elements. Since the current sensor is connected in a DC supply lead between the smoothing capacitor and the semi-conductor switching elements, one detects not only an excess current during discharge of the smoothing capacitor but also an excess current during normal operation. An error signal can thus be obtained which brings about a corresponding drop in the regulated DC voltage.

A monostable multivibrator can be provided to define the predetermined period.

Each semi-conductor switching element can be bridged by a respective free-running diode, the free-running diodes being connected to a point between the smoothing capacitor and the current sensor. In this way one does not detrimentally affect the function of the current sensor and the means to conduct oppositely to the normal direction.

A starting circuit can be connected to the regulator signal generator to provide a gradual increase in the regulated DC voltage after the predetermined period. In this way one ensures that the voltage across the smoothing capacitor rises only gradually after a fault has presumably disappeared. If, for example, a short circuit should nevertheless still be in existence, this is detected by the current-sensor at a very low voltage across the smoothing capacitor. During the subsequent repeated drop in the capacitor voltage, the capacitor need only be slightly discharged.

The starting circuit can comprise a capacitor chargeable through a diode in response to the output of the disabling circuit and connected to an input of an amplifier arranged to control the regulator signal generator.

The current sensor can be connected in a monitoring circuit having a switching characteristic with hysteresis. By this means, a second lower predetermined value is defined for the current value at which the semi-conductor switching elements are allowed to conduct again after being disabled. The switching characteristic with hysteresis can be obtained by connecting the current sensor to a differential amplifier provided with positive feedback.

The regulator can comprise a switching transistor and the said semi-seconductor switching elements can be transistors, the regulator signal generator and the inverter signal generator can ach comprise a respective plurality of logic circuits and the disabling circuit can be connected to control at least one logic circuit in each generator to suppress the base voltage of the transistors.

Two or more parameter monitoring circuits can be provided to monitor at least one further parameter in addition to said current and the outputs of the parameter monitoring circuits can be commonly connected to the disabling circuit. Various errors can desirably be taken into account by lowering the voltage across the smoothing capacitor.

One of the parameter monitoring circuits can be an over-voltage monitoring circuit arranged to detect when the voltage applied to the series regulator exceeds a predetermined value. In factories having very large motors, switching on and off of the latter can give rise to very high voltage transients of for example 200V in the mains, these lasting for several cycles and being potentially dangerous for the semi-conductor switching elements, particular transistors. Actually, all that is important is to switch off the series regulator. However, a discharge of the smoothing capacitor would be harmless.

One of the parameter monitoring circuits can be an under-voltage monitoring circuit arranged to detect when the voltage applied to the series regulator is less than a predetermined value.

The over-voltage monitoring circuit can comprise a differential amplifier one input of which is arranged to receive a signal proportional to the supply voltage to the series regulator, and the under-voltage monitoring circuit can comprise another differential amplifier one input of which, of opposite kind to the one input of the over-voltage differential amplifier, is arranged to receive a signal proportional to the supply voltage to the series regulator, each of the other inputs of the differential amplifiers being arranged to receive a reference voltage.

One of the parameter monitoring circuits can be an earth current monitoring circuit arranged to detect the occurrence of an earth fault.

Contact with earth generally leads to one of the two D.C. connecting leads being applied to earth potential. This gives rise to a corresponding increase in potential of the other D.C. connecting lead by reason of the voltage applied to the smoothing capacitor. It is therefore desirable to reduce this voltage by discharging the smoothing capacitor.

Advantageously, it is ensured that the earth current monitoring circuit comprises a transformer connected to the output of the inverter and arranged to feed a capacitor and a parallel discharge resistor through a rectifier circuit, and a comparator circuit is arranged to receive the voltage across the last-mentioned capacitor as an input. Preferably the last-mentioned comparator circuit has a hysteresis switching characteristic. The continuance of the earth fault is thereby detected only in certain time intervals and discharging of the smoothing capacitor can take place therebetween.

Preferably each parameter monitoring circuit comprises a respective differential amplifier with positive feedback and a switching characteristic with hysteresis.

An inverter circuit constructed in accordance with the invention will now be described by way of example only with reference to the accompanying drawings, in which:

Fig. 1 is a simplified circuit diagram of part of an inverter circuit with various parameter sensors;

Fig. 2 is a block diagram of a protective circuit forming the remainder of the inverter circuit;

Fig. 3 shows various waveforms appertaining to the conditions during the occurrence of a short circuit; and

Fig. 4 shows several waveforms appertaining to the conditions on the occurrence of an earth fault.

Referring to Figure 1, an inverter has terminals 1 (positive) and 2 (negative) to which, in use, is applied a constant D.C. voltage U= which can for example be obtained from a three-phase voltage by a rectifier bridge followed by a filter capacitor. A voltage divider consisting of two resistors R1 and R2 is connected to the terminals. A signal voltage u_1 proportional to the constant D.C. voltage U= is obtained across the resistor R2.

A series switching regulator 3 comprises a transistor Tr1 which is switched by the voltage developed across a resistor R3 when a regulating signal of adjustable pulse width or frequency is applied to terminals k1 and k2. This series regulator therefore operates as a chopper controlled according to pulse width or frequency.

An intermediate circuit 4 comprising a filter or smoothing capacitor C1 and a smoothing choke L1 is connected to the output of the controller 3. A regulated smoothed D.C. voltage U_r therefore occurs at the output of this intermediate circuit.

The voltage U_r is fed to a three-phase inverter 5 which comprises three pairs of series-connected transistors Tr2, Tr3; Tr4, Tr5; and Tr6, Tr7, each pair being connected in a respective one of three branches. Each transistor is associated with a respective one of diodes D1, D2, D3, D4, D5 and D6. Control of the transistors Tr2 to Tr7 is achieved by means of the voltage developed across respective ones of associated resistors R4 to R8 when an inverter control signal is applied to respective associated pairs of terminals. That pair of these associated terminals relating to transistor Tr2 is reference K3, K4 but the other pairs are not referenced. Extending from the centre point of each inverter branch there is a phase line 6, 7 or 8 leading to a load 9, which may in particular be an A.C. motor. On the terminal 1 or positive side, the transistors Tr2, Tr4 and Tr6 and the associated diodes D1, D3, and D5 are connected to a common D.C. connnecting lead 10. On the terminal 2 or negative side, the transistors Tr3, Tr5 and Tr7 have a common D.C. connnecting lead 11 whilst the associated diodes D2, D4 and D6 are connected to a separate lead 12.

In a line 13 making connection to both the lines 11 and 12 there is a sensor resistor R9 through which a current signal i_1 flows and can be sensed as a voltage across the resistor this current corresponding to the total direct current. This sensor is therefore referred to as the operating current sensor 14.

A sensor resistor R10 and an inductor

L2 lie in series with the D.C. connecting line 11. This series network comprising resistor R10 and choke L2 is bridged by a diode D7 which is poled oppositely to the normal direction of the operating current. Therefore the current that previously flowed through the transistors Tr2 to Tr7 will flow through the sensor resistor R10. This sensor is used as an excess current sensor and is referenced 15.

Associated with the three-phase lines 6, 7 and 8 there is a summation transformer T1 which is linked with all three phases. The transformer T1 has a secondary winding connected by a rectifier arrangement D8 which feeds a capacitor C2 in parallel with a discharge resistor R11. The capacitor voltage serves as earth fault current signal i_3. The entire arrangement is therefore an earth fault sensor 16.

The protective circuit of the inverter is shown in Figure 2 and includes a regulator signal generator 17 having outputs referenced K1 and K2 for connection to the identically-referenced regulator inputs k1 and k2. This regulator signal generator is controlled by a current regulator 18 in such a way that that current defined by the setting of a potentiometer P1 just flows in the intermediate filter circuit at the voltage U_r that is produced. For this purpose the regulator signal generator has a differential amplifier A1 to the inverting input of which the operating current signal i_1 is applied by way of a resistor R12 and an operating voltage U_2 is applied by way of the potentiometer P1. The non-inverting input is connected to earth by way of a resistor R13. The regulator signal generator can also be influenced by other parameters, as is indicated diagrammatically by input lines 19, for example by the voltage U_r, the motor frequency or any other desired parameters.

To control the transistors Tr2 to Tr7 in the inverter 5 there is an inverter signal generator 20 which is fed with input signals by way of at least one line, three input lines 21 are shown, particularly in respect of the desired frequency. Pulses bringing the transistors Tr2 to Tr7 to the conductive state then occur in the correct phase relationship and for the correct period at the outputs which correspond to the inputs k3 and k4 of the transistors Tr2, as well as the unferenced inputs of the other transistors Tr3 to Tr7.

The outputs of four differential amplifiers A2, A3, A4 and A5 are connected to a common error signal line 22. These differential amplifiers constitute an excess current comparator 23, an earth current comparator 24, an under-voltage comparator 25 and an excess voltage comparator 26. The excess current signal i_2 is fed to the excess current comparator A2 at its inverting input. The non-inverting input is connerted to the tapping of a voltage divider consisting of two resistors R14 and R15 connected between a voltage U_s and earth. A further resistor R16 provides positive feedback.

The earth current amplifier A3 is fed at its inverting input by an earth current signal i_3 whilst the non-inverting input is again fed with the voltage U_s of the control circuit by way of a voltage divider comprising resistors R17 and R18. A resistor R19 provides positive feedback.

The inverting input of the under-voltage amplifier A4 is connected directly to a reference voltage U_3 and the non-inverting input of the excess voltage amplifier A5 is connected also to the voltage U_3 but by way of a resistor R20. The voltage signal U_1 proportional to the D.C. voltage U= is connected to the non inverting input of the under-voltage amplifier A4 by way of a resistor R21 and to the inverting input of the excess voltage amplifier A5 by way of a resistor R22. Each amplifier has a respective positive feedback resistor R23, R24. The error signal line 22 is connected to the voltage U_s of the control circuit by way of a resistor R25.

If an error signal *f* occurs on line 22, the delivery of control pulses to the transistors Tr2 to Tr7 is immediately suppressed in the inverter signal generator 20 so that these transistors are in a non-conducting state. At the same time a monostable multivibrator 27 is actuated which produces a stop signal *s* of predetermined duration on a line 28. This stop signal immediately suppresses the delivery of pulses in the regulator signal generator 17 so that the series regulator 3 is also in a non-conducting state.

Simultaneously, a capacitor C3 in parallel with the resistor R13 at the non-inverting input of the amplifier A1 is charged by way of a diode D9 and a resistor R26. The voltage at this input is therefore raised by the capacitor voltage. The non-inverting input voltage reduces gradually after termination of the stop signal *s* by the capacitor C3 discharging through the resistor R13.

To explain the operation, a short circuit will first of all be considered as having occurred in the load and having been detected by the excess current sensor 15. In Fig. 3 there are shown above one another against time: the current i_2 sensed as a voltage across resistor R10 corresponding to the current flowing through the transistors (waveform *a*), the current I_{D7} flowing through the rectifier D7 (waveform *b*), the voltage U_r at the intermediate filter circuit (waveform *c*), the stop signal *s* (waveform *d*), and the error signal inverter $\overline{f}$ (waveform *e*).

Prior to the instant t_1 the circuit is in normal operation. At the instant t_1, the excess current comparator 23 detects the presence of an excess current. The error signal *f* is produced immediately and the stop signal *s* is initiated. The inductor L2 attempts to maintain that current flowing through itself at the time of initiation of the stop signal *s* and sends current through the diode D7. After a certain time, the current through resistor R10 drops to below a lower limiting value defined by amplifier A2 which has a switching characteristic with hysteresis and the error signal *f* disappears at the instant t_2. The inverter signal generator 20 now operates normally. Consequently the transistors Tr2 to Tr7 are brought to the conductive state in the correct sequence. For this reason the capacitor C1 discharges through the transistors and the load as well as the inductor L2 and the sensor resistor R10. Because of the inductance, the current rises only gradually. At the instant t_3, it again attains the limiting value at which the excess current comparator 23 responds. The resulting error signal *f* again blocks the inverter. The current through the inductor L2 is maintained for a while by way of the diode D7. At the instant t_4, the excess current amplifier A2 switches back. The error signal *f* disappears. The smoothing capacitor C1 can again discharge through the inverter. Since its voltage capacitor C1 can again discharge through the inverter. Since its voltage had already dropped, it this times take longer before the maximum current value is again reached at the instant t_5, whereby the inverter is again blocked. Its conductivity occurs at the instant t_6. Since the capacitor is fully discharged and the series regulator 3 remains blocked, no disturbing current will now flow. At the end of the stop signal *s*, that is at the instant t_7, the regulator signal generator 17 can again commence to operate. However, the D.C. regulator 18 will set only a small current i_1 because the capacitor C3 has been charged, and, because of the gradual discharge of the capacitor C3, this current increases considerably more slowly than is the case for the normal time constant of the inverter, thus there will be only a gradual increase in the voltage U_r. If the short circuit has not yet been eliminated, an excess current will very soon be detected by the amplifier A2, namely at the instant t_8.The voltage U_r will amount to only 5 to 10% of the maximum voltage so that the subsequent discharge of the capacitor C1 takes place rapidly. It is completely discharged by the instant t_9. A renewed attempt at starting up occurs at the end of the stop signal *s* at the instant t_{10}. If there is now no short circuit, the voltage U_r rises to the desired value with the illustrated small gradient.

The conditions with an earth current will be considered in conjunction with Fig. 4. Here there are shown above one another the ear current I_e (waveform *a*), the signal voltage i_3 at the capacitor C2 (waveform *b*), the stop signal *s* (waveform *c*) and the inverted error signal $\bar{f}$ (waveform *d*). On the occurrence of an earth current, the summation transformer T1 will respond. From the instant t_{11}, the capacitor C2 is charged. At the instant t_{12}, the signal i_3 exceeds the upper limiting value g_o of the earth current amplifier A3 having switching hysteresis. By reason of the occurrence of the error signal *f* the stop signal *s*, the series regulator 3 and the inverter 5 are blocked. The earth current I_e dies away up to the instant t_{13}. The capacitor C2 was being charged up to this time. It is subsequently discharged through the resistor R11. As soon as the signal i_3 drops below the lower limiting value g_u, which occurs at the instant t_{14}, the inverter again becomes conductive. The smoothing capacitor C1 can discharge partially in the manner described in relation to the excess current. However, the earth current I_e will again rise simultaneously so that a short time later, namely at the instant t_{15}, the amplifier A3 will again give the error signal *f*. The conditions as just described are repeated. When the stop signal *s* terminates at the instant t_{16} and the earth current has disappeared, normal operation will follow. If the earth current is still present, an error signal *f* will again be produced to release a stop signal *s* and repeat the aforementioned procedure.

Should there be any direct current components caused by the earth fault, they are detected by the excess current sensor R10.

On the occurrence of an under-voltage, the under-voltage comparator 25 will give an error signal *f* until the normal voltage has again been established. The excess voltage comparator 26 gives an error signal *f* when the input voltage is too high. This ensures that the inverter will operate only when the voltage is held constant within predetermined limits.

WHAT WE CLAIM IS:—

1. An inverter circuit comprising:

a series switching regulator connected to a smoothing capacitor and controllable by a signal of variable pulse width and/or frequency to feed a regulated DC voltage to semi-conductor switching elements selectively switchable to derive an AC voltage from the regulated DC voltage,

a regulator signal generator to provide a signal of variable pulse width and/or frequency to control the regulator,

an inverter signal generator to provide switching signals for the semi-conductor switching elements, a current sensor connected in series with an inductor in a DC supply lead between the smoothing capacitor and the semi-conductor switching elements, the current sensor and inductor being bridged by means to conduct in the opposite direction to the normal direction of current flow through the sensor, and

a disabling circuit operative on detection, by a parameter monitoring circuit including the current sensor, of current sensed by the current sensor exceeding a predetermined value to prevent the inverter signal generator from switching on said semi-conductor switching elements whilst the predetermined value is exceeded and the regulator signal generator from switching on the regulator for a predetermined period to allow the smoothing capacitor to discharge.

2. A circuit as claimed in claim 1, wherein a monostable multivibrator is provided to define the predetermined period.

3. A circuit as claimed in claim 1 or 2, wherein each semi-conductor switching element is bridged by a respective free-running diode, the free-running diodes being connected to a point between the smoothing capacitor and the current sensor.

4. A circuit as claimed in any preceding claim, wherein a starting circuit is connected to the regulator signal generator to provide a gradual increase in the regulated DC voltage after the predetermined period.

5. A circuit as claimed in claim 4, wherein the starting circuit comprises a capacitor chargeable through a diode in response to the output of the disabling circuit and connected to an input of an amplifier arranged to control the regulator signal generator.

6. A circuit as claimed in any preceding claim, wherein the current sensor is connected in a monitoring circuit having a switching characteristic with hysteresis.

7. A circuit as claimed in claim 6, wherein the current sensor is connected to a differential amplifier provided with positive feedback.

8. A circuit as claimed in any preceding claim, wherein the regulator comprises a switching transistor and the said semi-conductor switching elements are transistors, the regulator signal generator and the inverter signal generator each comprise a respective plurality of logic circuits and the disabling circuit is connected to control at least one logic circuit in each generator to suppress the base voltage of the transistors.

9. A circuit as claimed in any preceding claim, wherein two or more parameter monitoring circuits are provided to monitor at least one further parameter in addition to said current and the outputs of the parameter monitoring circuits are commonly connected to the disabling circuit.

10. A circuit as claimed in claim 9, wherein one of the parameter monitoring circuits is an over-voltage monitoring circuit arranged to detect when the voltage applied to the series regulator exceeds a predetermined value.

11. A circuit as claimed in claim 9 or 10, wherein one of the parameter monitoring circuits is an under-voltage monitoring circuit arranged to detect when the voltage applied to the series regulator is less than a predetermined value.

12. A circuit as claimed in claims 10 and 11, wherein the over-voltage monitoring circuit comprises a differential amplifier one input of which is arranged to receive a signal proportional to the supply voltage to the series regulator, and the under-voltage monitoring circuit comprises another differential amplifier one input of which, of opposite kind to the one input of the over-voltage differential amplifier, is arranged to receive a signal proportional to the supply voltage to the series regulator, each of the other inputs of the differential amplifiers being arranged to receive a reference voltage.

13. A circuit as claimed in any of claims 9 to 12, wherein one of the parameter monitoring circuits is an earth current monitoring circuit arranged to detect the occurrence of an earth fault.

14. A circuit as claimed in claim 13, wherein the earth current monitoring circuit comprises a transformer connected to the output of the inverter and arranged to feed a capacitor and a parallel discharge resistor through a rectifier circuit, and a comparator circuit arranged to receive the voltage across the last-mentioned capacitor as an input.

15. A circuit as claimed in any of claims 9 to 14, wherein each parameter monitoring circuit comprises a respective differential amplifier having positive feedback and a switching characteristic with hysteresis.

16. An inverter circuit substantially as herein described with reference to and as illustrated by the accompanying drawings.

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1583581 COMPLETE SPECIFICATION

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Sheet 1

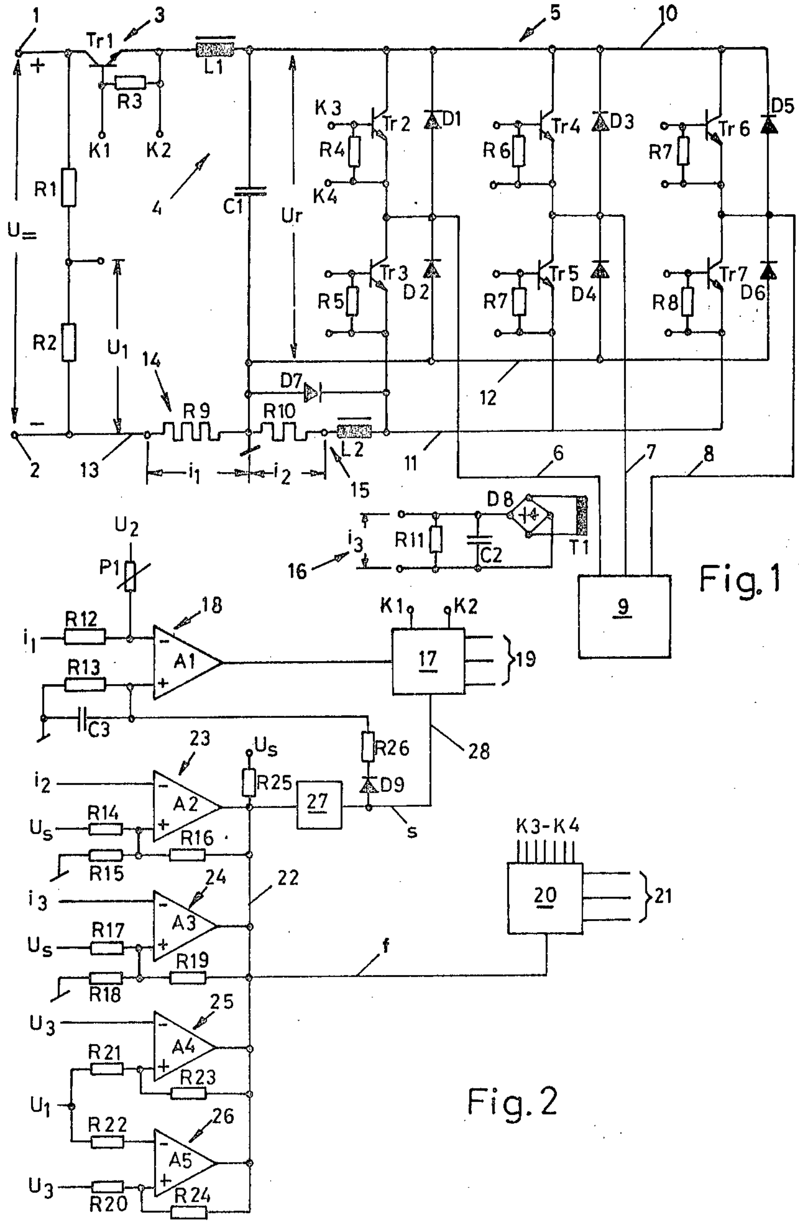

Fig. 1

Fig. 2

1583581 COMPLETE SPECIFICATION

2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 2

Fig.3

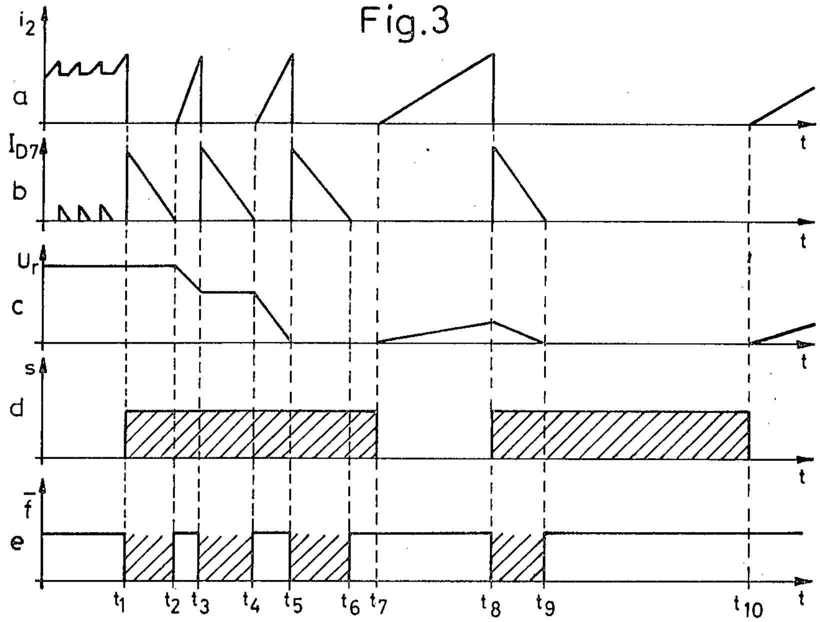

Fig.4