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(71) Applicant (*for all designated States except US*): **THE ENGINEERING BUSINESS LIMITED** [GB/GB]; Broomhaugh House, Riding Mill, Northumberland NE44 6EG (GB).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): **GRINSTED, Timothy, William** [GB/GB]; Beaumont House, Stocksfield NE43 7TN (GB). **SLEE, David** [GB/GB]; The Peth, Riding Mill NE44 6HL (GB). **O'LOUGHLIN, David** [GB/GB]; 5 Norwich Drive, Telford, Shropshire TF3 2NS (GB).

(74) Agent: **HARRISON GODDARD FOOTE**; Belgrave Hall, Belgrave Street, Leeds LS2 8DD (GB).

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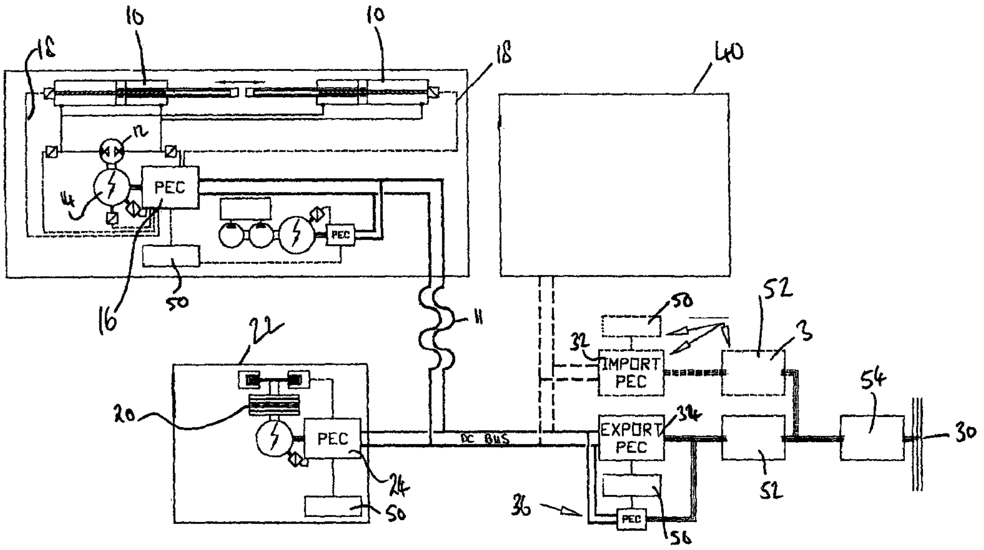
(54) Title: POWER TRANSFER APPARATUS AND METHODS



(57) Abstract: In a method of and apparatus for converting energy from natural energy sources into a more useable form of energy such as electrical energy, a sensor (10) is acted upon by the external energy source to cause movement of the sensor. Movement (10) of the sensor (10) is converted into a second form of energy such as electrical energy. A variable force is applied to the sensor (10), preferably under the control of one or more PECs (16). The variable force is *inter alia* controlled to achieve a desired load impedance of the sensor in order to maximise the efficiency of power transfer.

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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.

Power Transfer Apparatus and Methods

Background to the Invention

This invention relates to apparatus for the extraction of power, in particular from the natural environment and especially to the generation of energy from natural sources such as wind and tidal forces. More especially, the invention relates to means for and methods of maximising the efficiency of power transfer from a natural energy source

In the field of electricity generation in general there are many electricity generators which include moving parts that are acted upon by pre-existing external forces. By the provision of a resistance to the motion of those moving parts, it is possible to cause the external forces to do work, allowing electrical power to be generated. However, one difficulty in extracting useful power from external sources is that of providing sufficient, but not excessive, resistance against which the external forces will act.

The amount of power transferred in arrangements of the above type is the scalar product of the applied force and the velocity of movement of the moving part. In the case of rotary movement, the applied force is a torque and the velocity of movement is angular velocity. If the resistance to motion is too great, the external force will not be sufficient to cause any movement. The velocity (or angular velocity) will be zero and so the power transferred will be zero. An example of this scenario is a wind turbine with its brakes applied. The wind is unable to turn the rotor because insufficient torque is generated to overcome the brakes. No power is absorbed from the wind. Conversely, if there is no resistance to motion then there can be plenty of speed but still no power transferred. An example of this scenario is a controllable pitch propeller of a ship being set to zero angle of incidence. The propeller still turns but no water is moved in an axial direction and, other than that required to overcome drive train and churning losses, no power would be taken from the ship's engines.

Certain physical processes impose an upper limit on the amount of power that can be extracted from a source. For example in wind turbine applications the upper limit is known as Betz's limit. The practical application of such limits is the recognition that if the resistance to motion is either too great or too small, less than the theoretical maximum amount of power can be extracted or transferred. The key to maximising power transfer is setting the resistance to motion at exactly the right level. This can be thought of as matching the load impedance (equating to the resistance to motion) of the power transfer apparatus to the characteristics of the source.

It is possible to configure fixed physical parameters of a power extraction system to provide a particular load impedance most appropriate to the power source so that the power transfer from the source is maximised. However, should the nature of the source then change, it is quite likely that there will no longer be a good match between the extraction system and the source characteristics and that the power transfer will be less than the theoretical maximum. It can be readily appreciated that this problem is especially acute when the power source is a natural power source, such natural sources inherently having great variability. For these reasons, devices such as variable pitch turbines have been developed enabling optimisation of power extraction at fixed speed but varying torque. Other power extraction devices run at differing speeds to change their load impedance characteristics as seen by the source.

Summary of the Invention

The present invention takes a somewhat different approach. In accordance with a first aspect of the present invention there is provided a power transfer apparatus comprising:

i) a sensor, responsive to an external source of energy to cause movement thereof; and

ii) a device for converting movement of the sensor, optionally via an intermediate linkage or other intermediate power transfer mechanism, into a second form of energy, the device including means for applying a force to the sensor and further including control means for varying the applied force to achieve a desired load impedance of the sensor.

Preferably the external energy source is a natural energy source, such as for example wind, wave or tidal flow sources.

In much preferred embodiments, the second form of energy is electrical energy.

In another preferred embodiment, the control means comprises one or more power electronic controllers (PECs).

Preferably a PEC is operative to maintain the apparatus within a predetermined velocity profile in accordance with a pre-determined set of fixed apparatus parameters and outputs from the measurement of a predetermined set of variable apparatus parameters.

In one preferred variation, the apparatus of the invention further comprises an energy storage means and a PEC (which may be additional to the PEC controlling load impedance of the sensor) is operative to control transfer of energy to and from the energy storage means. In one example the energy storage means comprises a flywheel.

A PEC may preferably be operative to control deceleration of the sensor. Also one or more PECs may be operative to control dynamic braking of the sensor and to control transfer excess energy from said dynamic braking to an energy storage means.

In another form of the apparatus a PEC is operative to control transfer of energy from an energy storage means and to control acceleration of the sensor towards a desired speed by use of said stored energy. Separate PECs may control the energy transfer and the acceleration respectively.

In another variation of the apparatus according to this aspect of the invention a PEC is operative to control deceleration and/or displacement of the sensor such that it is brought to rest in a predetermined desired location.

In still another variation of the apparatus of this aspect of the invention a PEC operative to control the displacement and/ or speed and/or acceleration of a first sensor to maintain a predetermined desired phase relationship of said first sensor with second or further sensors.

In a further variation of the apparatus of this aspect of the invention a PEC is operative to prevent movement of the sensor beyond predetermined limits within the sensor's range of motion.

According to a second aspect of the present invention there is provided a method of converting energy from an external source into a second form of energy, the method comprising:

i) providing a sensor and converting said energy from an external source into movement of the sensor; and

ii) converting said movement of the sensor into a second form of energy, the method further comprising:

iii) applying a variable force to said sensor and controlling the applied force to achieve a desired load impedance of the sensor.

Preferably in the method of this aspect of the invention, the external energy source is a natural energy source.

Preferably the second form of energy is electrical energy.

In a particularly preferred embodiment of this second aspect of the invention, the application of said variable force is controlled by one or more PECs.

Preferably the method of this aspect of the invention further comprises the step of monitoring variable operational parameters of the sensor and controlling movement of said sensor by means of said variable applied force to maintain one or more of displacement, speed, acceleration and jerk of said sensor within predetermined limits.

In the present specification, unless the context requires otherwise, the term "sensor" relates to the moveable part of the apparatus which is in direct contact (sensing) with the external energy source and on which the external energy source acts to cause movement of the moveable part.

In the case of a rotary sensor, such as a turbine, the displacement is an angular displacement (angle) and the applied force is an angular force (torque).

Description of the Preferred Embodiments

In preferred embodiments, the invention makes use of power electronic converters (PECs). As is known in the art of power electronics, PECs are electronic devices which regulate the magnitude and direction of speed (or angular velocity) and force (or torque) of electric machines (linear and rotary) by various means including, but not limited to, creating variable frequency and variable voltage [simulated] AC and DC sources/sinks. Thus PECs, controlled by suitable software algorithms, can provide a means of adjusting load impedance of the sensor to control or regulate power extraction. In this sense, "to control or regulate" power extraction may include maximising the power extraction where possible and/or limiting power extraction (for example so that the apparatus does not exceed desired operational limits) or even reversing the power extraction (i.e. inputting power) where necessary or desirable. Examples of circumstances in which these options may be applicable are given below. By these means the net power extraction can be optimised in terms of efficiency of capture of power from the external (natural) power source whilst still accommodating particular requirements of the movement of the sensor and also accommodating forces applied by and to the sensor (including its intermediate systems) together with the physical limits of its power conversion capacity. Furthermore, since the load impedance is determined by software, any available output parameters, for example; force (torque), displacement (including all derivatives of displacement) and any mathematical or logical combinations of the available parameters can be made continuously variable during operation, enabling the power transfer apparatus of the invention to remain configured for optimal power transfer as the characteristics of the power source or the configuration or orientation of the apparatus vary.

When connected to a rotary (or linear) motor, a PEC can control both speed and torque (or force) in terms of magnitude and direction. Applying such a device to a power transfer apparatus (the motor thus acting as the device for converting movement of the sensor (via any intermediate linkage or other intermediate power transfer mechanism) into electrical energy, i.e. acting in this sense as a generator) enables seamless, co-ordinated, direct and independent control of resistance to motion when generating, of applied torque (or force) when driving the motor, and of speed of movement, displacement (or position), acceleration, deceleration and jerk (rate of change of acceleration) for both the generating and driving modes of operation. Such control is exercisable as required in order to maximise, limit or otherwise dictate the magnitude and direction of the net and instantaneous power transfer thereby enabling accommodation of the particular characteristics of the power transfer apparatus, the external energy source and any other consideration which may be pertinent to the apparatus, its environment and its application.

Apart from instantaneous and continuously variable control of load impedance, the approach adopted in the present invention also enables the following notable achievements:

(1) Acceleration control can be such that the moving parts of the power transfer apparatus can be accelerated using a reverse power flow. Such a facility has application, for example, where a cyclic motion is employed in the process of power

transfer, such as when extracting power from waves in coastal or offshore installations, where the natural power source fluctuates (such as when extracting power from wind) and where the power transfer rate is related to speed of the sensor. Using reverse (consumed) power to accelerate the sensor to an optimal initial speed enables generation to start at a significantly earlier point in the cycle than would otherwise be the case and therefore enables a greater net power conversion . A flywheel or other energy storing arrangement can be used to provide an energy source that can be drawn on to supply the reverse (consumed) power (i.e. power input) – the PEC acting in this situation as the means of controlling of the actual direction of power flow.

(2) Deceleration control of the moving parts of the power transfer apparatus can be such that dynamic braking is effected and controlled to be within the force (torque) and power limits of all the parts and components of the apparatus. Examples of this aspect of control include the avoidance of inducing hydraulic pressures high enough to cause relief valves to open or the avoidance of inducing electrical currents high enough to trip any circuit protection devices which may be present. Such a facility has particular application, for example, where a cyclic motion is employed with the sensor because such a power transfer apparatus must normally come to rest and reverse its direction twice in each cycle. At the point of reversal the kinetic energy of the moving part (sensor) has to be brought to zero. This kinetic energy can be gainfully converted by the PEC because the PEC can be controlled in such a way as to dictate that the instantaneous power output of the power transfer apparatus be greater than that instantaneous power input from the external source. The difference between the two powers will be provided by virtue of the deceleration of the moving parts thus making good use of the kinetic energy rather than allowing it to be wasted by dissipation in buffers or similar devices. In a variation, a (further) PEC may be used to change the frequency of the energy transferred by the sensor to a desired frequency which is directly compatible with a load where energisation is required (e.g. the local electricity grid, typically at 50Hz or 60Hz, but other frequencies being possible).

(3) Acceleration and deceleration control of the sensor by the PEC enables devices to come on stream and be taken off stream in a manner that minimises disturbances to other devices or systems. For example, control by the PEC allows turbines to be started without allowing the starting current to cause a significant dip in the output voltage of other devices which may be connected to the same electrical grid. Also, in a system which employs multiple transfer paths, when a given transfer path is not, at a given time, able to transfer energy efficiently control by the PEC allows additional energy to be transferred from another path which is still available for efficient energy transfer.

(4) Acceleration and deceleration control can be utilised to determine the limits of movement of a cyclic device such as, for example, any device which has a limited range of movement and which has to reverse direction upon, or before, reaching the end of stroke in each direction. By varying the position at which deceleration starts and the rate of that deceleration the extremities of the motion profile become controllable. Such an approach is usefully taken to optimise net power transfer or limit peak power transfer by preventing the generator operating in regions of poor or excessive power resource, that is ensuring operation in regions of effective or attainable resource. An example of this aspect of control is a tidal stream generator with a vertically moving sensor which, as far as possible, needs to avoid operation close to the surface where the water flow can start to bypass (flow over the device) rather than impinge upon (flow through) it. A further complication, in this instance, being that for a device installed on the sea bed the position of the water surface varies according to the state of the tide. By employing software to control (via the PEC) the limits of movement of the sensor it becomes possible for this varying constraint to be readily accommodated. Similarly the limits of movement may be constrained for other practical reasons not associated with power take off but, for example, to allow access or clearance around moving parts.

(5) Control of acceleration, deceleration and jerk can have a beneficial effect by limiting shock loadings which enables lighter structures to be used than would otherwise be the case for any particular power output rating. Conversely the fatigue life or rated power of existing structures or designs can be enhanced. Again the required control is available by means of a PEC operating with appropriate software.

(6) Displacement (and speed) control can be such that a device is held in any particular position for the purposes of maintenance, or to control the phasing of adjacent or associated devices to limit interaction or power disturbances or ripple. For example, a multi-bladed turbine can be brought to rest in a particular position to enable maintenance crews access to any specific blade. In a multiple installation, or 'farm' of devices which exhibit an inherent ripple in their individual power outputs, such as caused when the blades of a wind turbine pass in front of the nacelle support column, then PEC controlled phasing of the devices can be used to ensure that no two blades (on different turbines) pass the column at the same time. The individual power ripples are unaltered but the resultant ripple in the net (farm) power output can be reduced and controlled. In another example, safe shut-down of a device for extracting power from a tidal flow can be achieved by ensuring that the control member (on which the tidal flow acts and which is caused to move by the tidal flow) is brought to rest close to the seabed.

(7) Speed control can be effected independently of load impedance control to cater for external or internal constraints. For example: it may be necessary to limit the speed of a turbine blade to prevent tip cavitation; it might be advantageous to skip through certain velocities to avoid dwelling at resonance frequencies; or there may be speed-related (rather than power-related) limitations in the power transfer mechanisms.

When a suitable collection of the above parameters is gathered together it is convenient to express these as a "velocity profile", i.e. a definition of the speed and direction of the sensor of the power transfer apparatus at any instant in time.

Integration of this function gives a representation of position at any instant. Differentiation of the function gives a representation of the acceleration or deceleration at any instant and further differentiation of the function gives a measure of jerk. Alternatively the collection of parameters can be represented as a displacement profile or an acceleration profile, but since PECs are devices which have evolved as speed controllers, using a velocity profile is the most convenient starting point in establishing control of load impedance and power absorption optimisation or limitation.

When velocity profile control is established on a device which also has variable gain (i.e. an ability for adjustment of the degree to which the sensor(s) can influence the external force and, similarly, an ability for adjustment of the degree to which the external force can influence the sensor(s)), such as is the case with controlled pitch turbines, it is possible to map the control of the variable elements to maximise power transfer within the complete set of limits under which the device is constrained, i.e., external limits, such as Betz's limit, and internal limits, such as maximum permissible speeds, acceleration/deceleration, jerk and displacements. By establishing a velocity profile which is the optimum movement locus of the device the variable element control can be configured to maximise the effort that would be required to force the device to depart from that velocity profile. Information from the PEC and/or from other sources indicates the generated power and the proximity to the limits placed on the apparatus by the physical constraints which then enables a closed loop control to be established, thus maximising power conversion without exceeding the predefined limits or constraints. By this means the load impedance of the device can automatically be set to the optimum point.

Thus, the present invention distils all of the fixed and variable constraints and requirements of the sensor and associated intermediate systems (linkages or other intermediate power transfer mechanisms) of an electricity generator into a velocity profile which can be effected by a PEC. Variable gain elements of the power extraction sensor are controlled. The proximity of instantaneous machine parameters are measured against the pre-defined, calculated or emerging limits to effect closed loop control using feedback provided by the PEC itself and/or from other sources. The outputs of the closed loop may be a change to the velocity profile itself, a change to the setting of the variable gain elements or a combination of both.

In controllable pitch turbine-derived power extraction, for example from tidal or other flowing fluid sources such as wind, the ability to control the speed and torque of the rotor gives an added dimension to the control which enables power generation to continue at heads or fluid velocities which would otherwise be too low. This extends the generation period for any installation and increases profitability and energy capture and decreases the cost of energy capture for the same investment.

In oscillation-derived power extraction devices, i.e., those with sensors which must stop and reverse because of existing or desirable limits to the extent of movement, the ability to control the speed, resistive torque or force and position of the moving elements enables energy capture to be optimised, controlled and/or limited, including energy capture and re-injection from an energy store such as a flywheel of the kinetic energy associated with the velocity of the moving parts of the power transfer apparatus. Control of the position of moving elements allows the phase relationship between a number of generators, such as wind turbines, to be controlled to reduce the net power output ripple.

An example of the application of the present invention to oscillation-derived power extraction is illustrated in Figure 1, which shows a pair of linked hydraulic rams (10) operated in tandem by a tidal flow power extraction device (not shown) of the type illustrated and described in international patent application no. PCT/GB99/00573, the contents of which are hereby incorporated into this application by reference. The oscillating flow of oil caused by movement of these hydraulic rams is converted by means of a hydraulic motor (12) into rotation of the rotor of an electric motor (14) (electricity generator). A PEC (16) is used to vary the forces acting to oppose this rotation of the rotor, thus varying the amount of electricity generated by a given angular displacement, whilst maintaining control over the movement of the moving parts, in this case the pistons in the hydraulic rams. Generated electricity is transferred by way of sub-sea cables (11).

Information is provided to the PEC (16) by means of a series of transducers, such as position transducers on the hydraulic rams (10), pressure transducers in the hydraulic lines (18) running from the hydraulic rams to the hydraulic pump, and speed and temperature transducers on the electric motor (14). This additional information facilitates adaptive control of the system to prevent it from operating in undesirable states, such as reaching the end of stroke of the rams (10), excessive hydraulic fluid pressure etc.

Also shown is an energy storage means (22) including a flywheel (20). The means (22) provides an energy store that can be drawn on for the purpose of acceleration control of the sensor (in this case part of the tidal stream generator) using reverse power flow as described above. The flywheel (20) is also used for smoothing the onward flow of power to the electricity (30) grid by acting as a short term energy store to smooth out the ripples in the power output of the generator .

Other generating means (40) may work in co-operation or combination with the tidal stream generator. Such means (40) include, by way of example, additional tidal stream generators, wind turbines, fossil fuel systems, biomass systems, photovoltaic systems and wave power systems. Additional PEC are provided for control of various parts of the system including a PEC (24) for contol of the energy storage means (22) and PECs (32) (34) for controlling import and export of energy from the local grid (30) and PEC (36) for "black start" (initial) power supply control. Other ancillary equipment may be provided as required such as communications equipment (50), switchgear (52) and transformers, meters etc (54)

Claims

1. A power transfer apparatus comprising:
   iii) a sensor, responsive to an external source of energy to cause movement thereof; and
   iv) a device for converting movement of the sensor, optionally via an intermediate linkage or other intermediate power transfer mechanism, into a second form of energy, the device including means for applying a force to the sensor and further including control means for varying the applied force to achieve a desired load impedance of the sensor.

2. An apparatus as claimed in claim 1 wherein the external energy source is a natural energy source.

3. An apparatus as claimed in claim 1 or claim 2 wherein the second form of energy is electrical energy.

4. An apparatus as claimed in any preceding claim wherein the control means comprises one or more power electronic controllers (PECs).

5. An apparatus as claimed in claim 4 wherein a PEC is operative to maintain the apparatus within a predetermined velocity profile in accordance with a predetermined set of fixed apparatus parameters and with outputs from the measurement of a predetermined set of variable apparatus parameters.

6. An apparatus as claimed in claim 4 or 5 further comprising an energy storage means wherein a PEC is operative to control transfer of energy to and from the energy storage means.

7. An apparatus as claimed in claim 6 wherein the energy storage means comprises a flywheel.

8. An apparatus as claimed in any of claims 4 to 7 wherein a PEC is operative to control deceleration of the sensor.

9. An apparatus as claimed in claim 8 wherein a PEC is operative to control dynamic braking of the sensor and to control transfer excess energy from said dynamic braking to an energy storage means.

10. An apparatus as claimed in any of claims 4 to 9 wherein a PEC is operative to control transfer of energy from an energy storage means and to control acceleration of the sensor towards a desired speed by use of said stored energy.

11. An apparatus as claimed in claim 10 wherein a first PEC is operative to control transfer of energy from an energy storage means and a second PEC is operative to control acceleration of the sensor towards a desired speed by use of said stored energy.

12. An apparatus as claimed in any of claims 4 to 11 wherein a PEC is operative to control deceleration and/or displacement of the sensor such that it is brought to rest in a predetermined desired location.

13. An apparatus as claimed in any of claims 4 to 12 wherein a PEC operative to control the displacement and/ or speed and/or acceleration of a first sensor to maintain a predetermined desired phase relationship of said first sensor with second or further sensors.

14. An apparatus as claimed in any of claims 4 to 13 wherein a PEC is operative to prevent movement of the sensor beyond predetermined limits within the sensor's range of motion.

15. A method of converting energy from an external source into a second form of energy, the method comprising:

iv) providing a sensor and converting said energy from an external source into movement of the sensor; and

v) converting said movement of the sensor into a second form of energy, the method further comprising

vi) applying a variable force to said sensor and controlling the applied force to achieve a desired load impedance of the sensor.

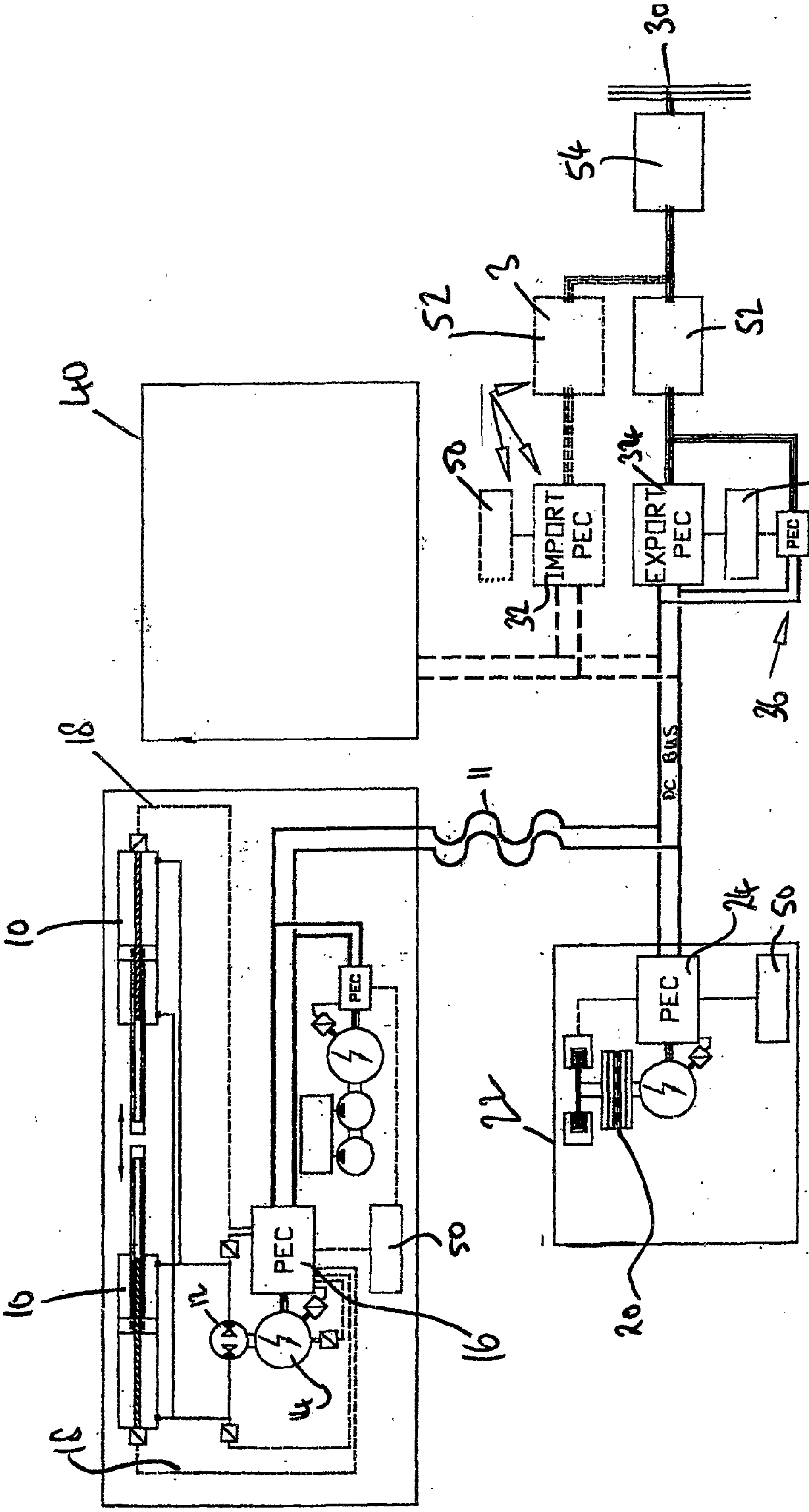
16. A method as claimed in claim 15 wherein the external energy source is a natural energy source.

17. A method as claimed in claim 15 or 16 wherein the second form of energy is electrical energy.

18. A method as claimed in any of claims 15 to 17 wherein the application of said variable force is controlled by one or more PECs.

19. A method as claimed in claim 18 including the step of monitoring variable operational parameters of the sensor and controlling movement of said sensor by means of said variable applied force to maintain one or more of displacement, speed, acceleration and jerk of said sensor within predetermined limits.

Figure 1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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 02/05379

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F03D7/02 F03B13/12

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)
IPC 7 F03D F03B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 155 375 A (HOLLEY WILLIAM E) 13 October 1992 (1992-10-13) column 4, line 42 - line 48 column 5, line 50 - line 63 column 6, line 30 - line 31 column 13, line 43 - line 57 figures 1,2,8	1-5,8,9, 12-19
X	US 5 083 039 A (RICHARDSON ROBERT D ET AL) 21 January 1992 (1992-01-21) column 1, line 68 -column 2, line 4 column 2, line 11 - line 16 column 6, line 3 - line 27 figures 1-3,5	1-5, 15-19

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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Date of the actual completion of the international search	Date of mailing of the international search report
17 February 2003	26/02/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Giorgini, G

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	PENA R S ET AL: "Vector controlled induction machines for stand-alone wind energy applications" PROCEEDINGS OF THE 2000 IEEE, XP010521302 page 1409, right-hand column, line 10 -page 1410, right-hand column, line 14 figures 1,2	1-5, 15-19
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