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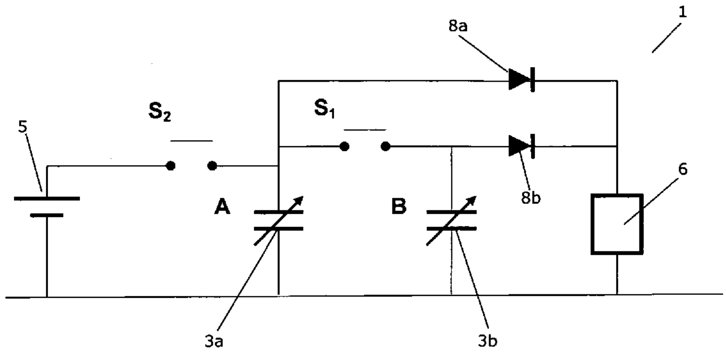

Fig. 2

(57) Abstract: A system and a method for generating electrical energy are disclosed. The system comprises at least two generator elements and a charge-discharge circuit. Each generator element comprises a first compliant electrode and a second compliant electrode arranged opposite to each other, thereby forming a capacitor, and each generator element is coupled to a mechanical energy input device arranged to supply mechanical energy to said generator element. The charge-discharge circuit is arranged to control charge and discharge of the compliant electrodes of the generator elements, said charge-discharge circuit being connected to an external electrical load. The at least two generator elements and the charge-discharge circuit are electrically interconnected in such a manner that electrical energy can be transferred directly between the generator elements, without being transferred via the external electrical load. The electrical energy transferred from one generator element during discharge is used for charging one or more other generator elements. The energy losses of the system are reduced, and an efficient system is obtained without the requirement for complicated electronic circuitry.

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A SYSTEM AND A METHOD FOR GENERATING ELECTRICAL ENERGY

FIELD OF THE INVENTION

The present invention relates to a system and a method for generating electrical energy. More specifically the present invention relates to a system and a method for converting mechanical energy into electrical energy. The system and the method of the invention reduce the energy losses occurring during the conversion of mechanical energy into electrical energy as compared to prior art systems and methods, thereby improving the system efficiency.

BACKGROUND OF THE INVENTION

Conversion between mechanical and electrical energy has previously been obtained using devices or systems comprising a so-called dielectric electro active polymer element (DEAP). A DEAP comprises two oppositely arranged compliant electrodes mounted on or applied to a substrate made from a resilient polymer material. The two electrodes form a capacitor with a capacitance depending on the areas of the electrodes and the distance between the electrodes.

In a system as described above, the energy conversion from mechanical energy into electrical energy takes place by sequentially charging and discharging the electrodes and mechanically stressing and relaxing the electrodes. The mechanical stress can be obtained either by means of a pull force, stretching the electrodes, or by means of a push force compressing the electrodes.

In the case that the mechanical stress is obtained by means of a pull force, the energy conversion takes place in the following manner. Initially, mechanical energy is supplied to the system by applying a pull force, thereby stretching the electrodes. This causes a decrease in the distance between the electrodes, and possibly a change in the shape of the electrodes, thereby changing the capacitance of the capacitor formed by the electrodes. Then electrical charge is supplied to the electrodes from an external electrical load. Subsequently the electrodes are allowed to relax, and the electrodes will thereby restore their original size and shape, and the distance between the electrodes is increased, thereby changing the capacitance of the capacitor formed by the electrodes. Since the distance between the electrodes increases and the (projected) cross-sectional area of the electrodes decreases during this step, and the applied charge remains unaltered, the electrical energy stored in the capacitor is increased while the mechanical energy decreases as a result of the relaxation of the electrodes. Finally, the electrodes are discharged to the external electrical load, before the cycle is restarted by once again applying mechanical energy to the electrodes. Some of the electrical energy discharged to the electrical load is used for charging the electrodes during the next cycle.

In the case that the mechanical stress is obtained by means of a push force, the energy conversion takes place in the following manner. Initially electrical charge is supplied to the electrodes from an external electrical load. Then mechanical energy is supplied to the system by applying a push force, compressing the electrodes. This causes an increase in the distance between the electrodes, and possibly a change in shape of the electrodes, thereby changing the capacitance of the capacitor formed by the electrodes. Since the distance between the electrodes is increased and the (projected) cross-sectional area of the electrodes decreases during this step, and the applied charge remains unaltered, the electrical energy stored in the capacitor is increased as a result of the mechanical energy being supplied to the electrodes. Subsequently, the electrodes are discharged to the external electrical load. Finally the electrodes are allowed to relax, before the cycled is restarted by once again charging the electrodes by means of the external electrical load. Similarly to the situation described above, some of the electrical energy which is discharged to the external load is used for charging the electrodes during the next cycle.

In both the situations described above mechanical energy is converted into the electrical energy during a step where the distance between the electrodes is increased. As a consequence, the electrical energy supplied to the external electrical load during the discharging step exceeds the electrical energy required for charging the electrodes during the next cycle. Thus, electrical energy can be 'harvested' from the system, i.e. mechanical energy is input into the system and electrical energy is extracted from the system. However, during the step of discharging the electrical energy from the electrodes to the external electrical load, as well as during the step of charging the electrodes by means of the external electrical load, energy losses are introduced in the system. This is particularly the case during the part of the discharging step where the bias voltage is low and during the charging step. It is possible to control the discharging and charging in a manner which reduces the energy losses. However, this requires relatively complicated electronic circuitry, thereby increasing the costs of the system.

It is therefore desirable to provide a system and a method for converting mechanical energy into electrical energy, where the energy losses can be reduced without the requirement for complicated electronic circuitry.

DESCRIPTION OF THE INVENTION

It is an object of embodiments of the invention to provide a system for generating electrical energy, wherein the energy losses in the system are reduced as compared to prior art systems.

It is a further object of embodiments of the invention to provide a system for generating electrical energy, the system being operable with low energy losses and simple electronics.

It is an even further object of embodiments of the invention to provide a system for generating electrical energy, the system being operable at high efficiency while maintaining a simple structure.

It is an even further object of embodiments of the invention to provide a method for generating electrical energy, wherein energy losses introduced in the process are minimised.

According to a first aspect the invention provides a system for generating electrical energy, the system comprising:

- at least two generator elements, each generator element comprising a first compliant electrode and a second compliant electrode arranged opposite to each other, thereby forming a capacitor, and each generator element being coupled to a mechanical energy input device arranged to supply mechanical energy to said generator element, and

- a charge-discharge circuit arranged to control charge and discharge of the compliant electrodes of the generator elements, said charge-discharge circuit being connected to an external electrical load,

wherein the at least two generator elements and the charge-discharge circuit are electrically interconnected in such a manner that electrical energy can be transferred directly between the generator elements, without being transferred via the external electrical load.

The system according to the first aspect of the invention is for generating electrical energy. Thus, the amount of electrical energy which it is possible to retrieve from the system exceeds the amount of electrical energy which is supplied to the system. The electrical energy may, e.g., be converted from available mechanical energy being supplied to the system via the mechanical energy input device. This will be described further below.

The system comprises at least two generator elements. Each generator element comprises a first compliant electrode and a second compliant electrode, the electrodes being arranged opposite each other in such a manner that they form a capacitor. In the present context the term 'compliant' should be interpreted to mean that each of the electrodes is flexible as well as stretchable and/or compressible. Thereby mechanical energy can be stored in the electrodes by stretching or compressing them. Stretching or compressing the electrodes preferably results in a change in the distance between electrodes and in the (projected) cross-sectional area of the electrodes, and thereby a change in the capacitance of the capacitor being formed by the electrodes. Thus, the generator elements are adapted to transform mechanical energy into electrical energy, i.e. to generate electrical energy. Each of the generator elements may advantageously be of the kind used in prior art systems and described above.

The mechanical energy being supplied to the system may advantageously be originating from a source which is readily available to the system, such as vibrations, waves, wind or human movements, etc. Thereby mechanical energy which would otherwise be wasted is utilised for generating electrical energy by means of the system according to the first aspect of the invention.

The charge-discharge circuit is arranged to control charge and discharge of the compliant electrodes of the generator elements. The charge-discharge circuit is connected to an external electrical load, thereby allowing the generator elements to be discharged to this load in order to 'harvest' electrical energy being generated by the generator elements. The external electrical load may, e.g., be a battery which is recharged during operation of the system.

The generator elements and the charge-discharge circuit are electrically interconnected in such a manner that electrical energy can be transferred directly between the generator elements without being transferred via the external electrical load. Thereby it is possible to transfer charge directly from one of the generator elements to one or more of the other generator elements. Accordingly, it is not necessary to entirely, or almost entirely, discharge the generator elements to the external electrical load, nor is it necessary to charge the generator elements from the external electrical load. Thereby the energy losses introduced during the last part of the discharging step and during the charging step in the method described above when using a prior art system are avoided. As a result, the system according to the invention operates more efficiently and the energy losses introduced by the system are considerably reduced as compared to prior art systems. Furthermore, this is obtained simply by interconnecting the generator elements and the charge-discharge circuit in such a manner that electrical energy can be transferred directly between the generator elements, i.e. without the requirement for complicated circuitry.

The charge-discharge circuit may be arranged to transfer a portion of electrical energy stored in a generator element to the external electrical load, and to transfer at least a portion of the remaining electrical energy stored in said generator element to one or more of the other generator elements. According to this embodiment, during discharge of a generator element, a portion of the electrical energy stored in the generator element is 'harvested', i.e. transferred to the external electrical load, while another portion is used for charging one or more of the other generator elements. Preferably, all or most of the remaining electrical energy is transferred to one or more of the other generator elements, thereby completely or almost completely removing all charge from the generator element being discharged. This reduces the energy losses introduced during transfer of mechanical energy to the generator element. It should, however, be understood that this embodiment also covers a situation where charge is left on the generator element.

The amount of electrical energy transferred to the external load may correspond to an amount of electrical energy being converted from mechanical energy input to the generator element during a working cycle for the system. According to this embodiment, the amount of energy which is 'harvested' from the system corresponds to the amount of energy being input to the system in the form of mechanical energy, and being transformed into electrical energy by the system. The amount of electrical energy being transferred to the other generator elements preferably corresponds to the amount of electrical energy supplied to the generator element during charging. One way to control the discharge of a generator element could be to discharge electrical energy to the external electrical load until the bias voltage left on the generator element substantially corresponds to a bias voltage required for charging one of the other generator elements, and then transfer the remaining electrical energy of the generator element to the generator element to be charged.

The mechanical energy input device may be adapted to provide forces stretching the compliant electrodes of at least one of the generator elements. This may be obtained by providing pull forces in the compliant direction of the electrodes. Alternatively, it may be obtained by pushing the electrodes towards each other, in a direction substantially transversely to the compliant direction of the electrodes, thereby squeezing material arranged between the electrodes and forcing the electrodes to stretch along the compliant direction. In any event, the stretching causes a decrease in the distance between the electrodes and an increase of the (projected) cross-sectional area of the electrodes, and thereby an increase in capacitance of the capacitor formed by the electrodes.

Alternatively or additionally, the mechanical energy input device may be adapted to provide forces compressing the compliant electrodes of at least one of the generator elements. This may be obtained by applying a push force along the compliant direction of the electrodes. Alternatively, it may be obtained by pulling the electrodes away from each other, in a direction substantially transverse to the compliant direction of the electrodes, thereby stretching material arranged between the electrodes and forcing the electrodes to compress along the compliant direction. In any event, the compression causes an increase in the distance between the electrodes and a decrease of the (projected) cross-sectional area of the electrodes, and thereby a decrease in capacitance of the capacitor formed by the electrodes.

The charge-discharge circuit may comprise at least one passive electronic component arranged to control discharge of electrical energy from one or more generator elements to the external electrical load. The passive electronic component may, e.g., be passive diode. Alternatively or additionally, the discharge of electrical energy from one or more generator elements to the external electrical load may be controlled using at least one active electrical component, such as a buck and boost circuit.

The charge-discharge circuit may further comprise at least one switch arranged to control transfer of electrical energy between the generator elements. The switch(es) may advantageously cooperate with the passive electronic component(s).

The switch(es) may advantageously be controlled on the basis of a voltage detected on one or more of the generator elements. In the case that the generator elements are of the kind which are stretched as a result of mechanical energy being supplied to the generator element, this may, e.g., be obtained in the following manner. When one of the generator elements is in a completely relaxed state and a mechanical force is applied in order to stretch the generator element, the voltage on the generator element decreases. This voltage decrease may be detected and used as an input to a switch which electrically interconnects two of the generator elements and allows charge to be transferred between the generator elements. Accordingly, it can easily be ensured that the charge transfer takes place at appropriate times during the operating cycle, and the control of the switches is independent of the stroke of the generator elements.

The charge-discharge circuit may further comprise an active electronic circuit cooperating with said switch(es) to control transfer of electrical energy between the generator elements. The active electronic circuit may, e.g., be a buck and boost circuit.

The system may further comprise a mechanical resonance system being mechanically coupled to the two or more generator elements in such a manner that mechanical energy can be transferred between each of the generator elements and the mechanical resonance system. The mechanical resonance system may comprise at least one mass and/or at least one spring member. According to this embodiment, some of the mechanical energy supplied to a generator element during a stretching or compressing step can be transferred to the mechanical resonance system during a relaxing step. This may, e.g., be desirable in the case that only part of the available mechanical energy is converted into electrical energy due to limitations, such as electrical breakdown strength of the materials used for the electrodes and electromechanical instability.

The mechanical energy thus transferred to the mechanical resonance system may subsequently be supplied to one of the other generator elements during a stretching or compressing step.

The resonance frequency of the mechanical resonance system may be tunable, e.g. by adjusting one or more springs of the resonance system.

The compliant electrodes of at least one of the generator elements may be in the form of metal layers applied to corrugated surfaces of elastomeric films. Such electrodes are very compliant.

According to a second aspect the invention provides a method for generating electrical energy using a system according to the first aspect of the invention, the method comprising the steps of sequentially:

- decreasing the distance between the compliant electrodes of a first generator element,

- providing a charge to the compliant electrodes of the first generator element by means of the charge-discharge circuit,

- increasing the distance between the compliant electrodes of the first generator element,

- discharging a portion of the electrical energy stored in the first generator element to the external electrical load, and

- discharging at least a portion of the remaining electrical energy stored in the first generator element to one or more of the remaining generator elements of the system.

It should be noted that a person skilled in the art would readily recognise that any feature described in combination with the first aspect of the invention could also be combined with the second aspect of the invention, and vice versa.

The method according to the second aspect of the invention is an operating cycle where the steps mentioned above are repeated. Thus, the distance between the compliant electrodes of the first generator element is initially decreased, further causing the (projected) cross-sectional area of the electrodes to increase. Thereby the capacitance of the capacitor formed by the electrodes of the first generator element is increased. While the distance is small and the capacitance high, a charge is provided to the compliant electrodes of the first generator element by means of the charge-discharge circuit. The charge may be supplied from an external power source or from one of the other generator elements. This will be described further below.

When the charging of the electrodes of the first generator element has been completed, the distance between the compliant electrodes of the first generator element is increased, further causing the (projected) cross-sectional area of the electrodes to decrease. Thereby the capacitance of the capacitor formed by the electrodes of the first generator element is decreased, and since the charge remains unaltered, the electrical energy stored in the first generator element is increased.

Finally the electrical energy stored in the first generator element is discharged. This is done by discharging a portion of the electrical energy to the external electrical load, and discharging at least a portion of the remaining electrical energy to one or more of the remaining generator elements, i.e. a portion of the electrical energy is used for charging one or more of the other generator elements, and this electrical energy is transferred directly between the generator elements. As described above, this is an advantage because the energy losses introduced by the system are thereby reduced, and a more efficient system is obtained.

The step of decreasing the distance between the electrodes may comprise applying a force to the compliant electrodes of the first generator element, causing the compliant electrodes to be stretched, and the step of increasing the distance between the electrodes may comprise allowing the electrodes to relax, thereby restoring their original size and shape. According to this embodiment, mechanical energy is supplied to the system during the step of decreasing the distance between the electrodes, and mechanical energy is converted into electrical energy during the step of increasing the distance between the electrodes. The applied force may, e.g., be a pull force applied along the compliant direction of the electrodes of the first generator element. As an alternative, it may be a force applied in a direction substantially transverse to the compliant direction of the electrodes, pushing the electrodes toward each other and forcing the material between the electrodes to expand along the compliant direction of the electrodes. This has been described in detail above.

Alternatively, the step of increasing the distance between the electrodes may comprise applying a force to the compliant electrodes of the first generator element, causing the compliant electrodes to be compressed, and the step of decreasing the distance between the electrodes may comprise allowing the electrodes to relax, thereby restoring their original size and shape. According to this embodiment, mechanical energy is supplied to the system during the step of increasing the distance between the electrodes, directly converting the mechanical energy into electrical energy during this step. The applied force may, e.g., be a push force applied along the compliant direction of the electrodes of the first generator element. As an alternative, it may be a force applied in a direction substantially transverse to the compliant direction of the electrodes, pulling the electrodes away from each other and forcing the material between the electrodes to contract along the compliant direction of the electrodes. This has been described in detail above.

The method may further comprise the steps of sequentially:

- decreasing the distance between the compliant electrodes of a second generator element,
- providing a charge to the compliant electrodes of the second generator element by discharging a portion of the electrical energy of the first generator element and transferring said electrical energy to the second generator element,
- increasing the distance between the compliant electrodes of the second generator element,
- discharging a portion of the electrical energy stored in the second generator element to the external electrical load, and
- discharging at least a portion of the remaining electrical energy stored in the second generator element to one or more of the remaining generator elements of the system.

According to this embodiment, the second generator element performs substantially the steps which are also performed by the first generator element, and which are described above. A portion of the electrical energy stored in the first generator element is transferred directly to the second generator element and used for charging the compliant electrodes of the second generator element.

The first generator element and the second generator element may be operated in such a manner that the step of discharging at least a portion of the remaining electrical energy stored in the first generator element to one or more of the remaining generator elements and the step of providing a charge to the compliant electrodes of the second generator element are performed substantially simultaneously. According to this embodiment, the first and second generator elements are operated synchronously in the sense that the first generator element is discharged exactly when the second generator element need to be charged, and charge can therefore readily be transferred from the first generator element to the second generator element, exactly at a time which is suitable with respect to operation of both generator elements. When the second generator element subsequently reaches the discharging step, this may advantageously be simultaneously with the charging step of the first generator element, or with one of the other generator elements.

The system may advantageously be operated in such manner that it is only necessary to supply electrical energy to the system upon initial charging of the first generator element. Afterwards, the generator elements are charged purely by means of electrical energy generated by the generator elements, and only mechanical energy shall be supplied to the system.

The method may further comprise the step of transferring mechanical energy to a mechanical resonance system during the step of increasing the distance between the electrodes or during the step of decreasing the distance between the electrodes. In this case the system comprises a mechanical resonance system as described above. It should be understood that mechanical energy is supplied to the mechanical resonance system during the step where the electrodes are allowed to relax. As described above, this may either be the step of increasing the distance between the electrodes or the step of decreasing the distance between the electrodes, depending on which kind of force is applied to the electrodes.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in further detail with reference to the accompanying drawings in which

Fig. 1 is a schematic view of a prior art system for generating electrical energy,

Fig. 2 is a schematic view of a system according to an embodiment of the invention,

Fig. 3 illustrates the operation of the system of Fig. 2

Fig. 4 illustrates the cooperation between the generator elements of the system of Fig. 2,

Fig. 5 illustrates energy transfer between generator elements of a system according to an embodiment of the invention,

Fig. 6 is a schematic view of two generator elements for use in a system according to an embodiment of the invention,

Fig. 7 is a schematic view of two generator elements for a system according to an embodiment of the invention, the system comprising a mechanical resonance system,

Fig. 8 is a schematic view of the system of Fig. 7, and

Fig. 9 is a schematic view of a system according to an embodiment of the invention, the system comprising four generator elements.

DETAILED DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view of a prior art system 1 for generating electrical energy. The system 1 comprises a generator element 2 comprising two oppositely arranged compliant electrodes forming a capacitor 3. A switch element 4 is arranged to be able to electrically connect the capacitor 3 to a voltage source in the form of a battery 5 or to an external electrical load 6. The generator element 2 is connected to a mechanical energy source arranged to provide a pull force to the generator element 2, thereby stretching the compliant electrodes of the capacitor 3. This is illustrated by arrow 7.

The system 1 of Fig. 1 is operated in the following manner. Initially a pull force is applied to the compliant electrodes of the generator element 2 as illustrated by arrow 7, thereby stretching the electrodes and decreasing the distance between them and increasing the (projected) cross-sectional area of the electrodes. Then the switch element 4 is moved to the left position, thereby establishing an electrical connection between the capacitor 3 of the generator element 2 and the battery 5. Thereby the capacitor 3 is charged by the battery 5. When the capacitor 3 has been charged to a desired bias voltage, the switch element 4 is moved to the position shown in Fig. 1, thereby disrupting the electrical connection between the capacitor 3 and the battery 5. Subsequently, the compliant electrodes of the generator element 2 are allowed to relax, thereby increasing the distance between the electrodes and decreasing the (projected) cross-sectional area of the electrodes. During this, the charge of the electrodes remains unaltered. Accordingly, the increased distance between the electrodes and the decreased (projected) cross-section area of the electrodes cause a decrease in the capacitance of the capacitor 3 and a corresponding increase in electrical energy stored in the generator element 2.

When the relaxation of the compliant electrodes has been completed, the switch element 4 is moved to the right position, thereby establishing an electrical connection between the capacitor 3 of the generator element 2 and the external electrical load 6. This causes substantially all of the electrical energy stored in the generator element 2 to be discharged to the external electrical load 6. The operating cycle of the system 1 is then repeated.

Since the electrical energy being discharged to the external electrical load 6 exceeds the electrical energy being supplied to the system 1 from the battery 5, the system 1 generates electrical energy on the basis of the mechanical energy supplied to the system 1 from the mechanical energy source.

Fig. 2 is a schematic view of a system 1 according to an embodiment of the invention. The system comprises a first generator element (not shown) and a second generator element (not shown). The first generator element comprises a first set of compliant electrodes forming a first capacitor 3a, and the second generator element comprises a second set of compliant electrodes forming a second capacitor 3b. The system 1 further comprises a first switch element S_1, a second switch element S_2, a battery 5 and an external electrical load 6. The first and second generator elements are connected to a mechanical energy source (not shown) which is arranged to supply mechanical energy to the compliant electrodes of the generator elements, similarly to the situation described above with reference to Fig. 1. Each of the generator elements is preferably of the kind or similar to the generator element 2 described above with reference to Fig. 1.

The first capacitor 3a is electrically connected to the external electrical load 6 via a first passive diode 8a, and the second capacitor 3b is electrically connected to the external electrical load 6 via a second passive diode 8b.

The switch pattern of the switch elements S_1, S_2 is shown in Fig. 3.

In the following the operation of the system 1 of Fig. 2 is described with reference to Fig. 2 and Fig. 3. At $T=t_0^0$ switch element S_1 as well as switch element S_2 is closed, i.e. switched on. This causes the electrodes of the first capacitor 3a, which have previously been stretched along their compliant direction, to be charged. Also the electrodes of the second capacitor 3b as well as the external electrical load 6 will be charged. At $T=t_1^0$ switch element S_1 as well as switch element S_2 is opened, i.e. switched off, and a mechanical force is applied to the compliant electrodes forming the second capacitor 3b, stretching the compliant electrodes, decreasing the distance between the electrodes and increasing the capacitance of the second capacitor 3b formed by the electrodes. Simultaneously, the compliant electrodes forming the first capacitor 3a are allowed to relax, increasing the distance between the electrodes and decreasing the capacitance of the first capacitor 3a formed by the electrodes. Thereby the electrical energy stored on the first capacitor 3a is increased. During this phase a portion of the increased electrical energy on the first capacitor 3a is discharged to the external electrical load 6 via passive diode 8a.

At $T=t_2^0$ switch element S_1 is closed, i.e. switched on, but switch element S_2 remains open, i.e. switched off. This causes the electrodes of the first capacitor 3a to discharge a portion of the remaining electrical energy stored on the first capacitor 3a directly to the compliant electrodes forming the second capacitor 3b, via switch element S_1. Thereby the electrodes of the second capacitor 3b are charged by means of the electrical energy stored on the first capacitor 3a, without the requirement of connecting the second capacitor 3b to the battery 5, i.e. without transferring additional electrical energy to the system 1.

At $T=t_3^0$ the switch element S_1 is opened, i.e. switched off, and a mechanical force is applied to the compliant electrodes forming the first capacitor 3a, stretching the compliant electrodes, decreasing the distance between the electrodes and increasing the capacitance of the first capacitor 3a formed by the electrodes. Simultaneously, the compliant electrodes forming the second capacitor 3b are allowed to relax, increasing the distance between the electrodes and decreasing the capacitance of the second capacitor 3b formed by the electrodes. Thereby the electrical energy stored on the second capacitor 3b is increased, allowing a portion of the increased electrical energy to be discharged to the external electrical load 6 via passive diode 8b, and the first operating cycle has been completed.

The next cycle is started by closing switch element S_1, but leaving switch element S_2 open, as illustrated in Fig. 3 as $T=t_0^n$. This causes the second capacitor 3b to transfer a portion of the electrical energy stored on the second capacitor 3b directly to the first capacitor 3a. Thus, the first capacitor 3a is charged directly by means of the electrical energy stored on the second capacitor 3b, and without the requirement for connecting the first capacitor 3a to the battery 5, i.e. without supplying additional electrical energy to the system 1. The switch element S_2 may be closed one time for each cycle.Thus, the steps described above are repeated, except for the initial step, connecting the electrodes of the first capacitor 3a to the battery 5. Accordingly, mechanical energy is supplied to the system during the steps of stretching the compliant electrodes of the capacitors 3a, 3b, and the system 1 generates electrical energy.

Fig. 4 further illustrates the operating cycle described above. Fig. 4 shows two plots of strain, i.e. stretching of the compliant electrodes or mechanical energy stored on the generator elements, and bias voltage, i.e. the electrical energy stored on the generator elements, during an operating cycle. The upper plot shows the operating cycle for the second capacitor 3b, and the lower plot shows the operating cycle for the first capacitor 3a. The times of switching the switch elements S_1 and S_2 on and off are indicated in Fig. 4.

It can be seen that during the charging step 9 the bias voltage is naturally increased. In addition, the strain is increased. This is because the positive charge applied to one electrode and the negative charge applied to the oppositely arranged electrode attract each other, thereby forcing the electrodes closer together, i.e. decreasing the distance, thereby increasing the strain in the system.

The relaxing step is divided into a first relaxing step 10 and a second relaxing step 11. During the first relaxing step 10 the strain is decreased while the bias voltage is increased. During the second relaxing step 11 the strain is decreased, but the voltage remains substantially constant. This is due to the fact that when the voltage on the capacitor increases above the voltage on the external electrical load, the electrical energy will be discharged from the capacitor to the external electrical load. The mechanical energy which is not converted into electrical energy may be transferred to a mechanical resonance system during the second relaxation step 11.

During the discharge step 12 the bias voltage is decreased and the strain is maintained substantially constant. During the stretching step 13 the strain increases and the bias voltage decreases. This is because a small charge remains on the generator element after the discharge step 12, and when the compliant electrodes are stretched during the stretching step 13, the bias voltage decreases, similarly to the mechanism described above with reference to the first relaxing step 10.

During the discharge step 12 of the first generator element (A) a portion of the electrical energy is discharged to the second generator element (B). Similarly, during the discharge step 12 of the second generator element (B) a portion of the electrical energy is discharged to the first generator element (A). This is illustrated by arrows 14. It should be understood that the discharge step 12 of the first generator element (A) takes place substantially simultaneously with the charging step 9 of the second generator element (B), and the discharge step 12 of the second generator element (B) takes place substantially simultaneously with the charging step 9 of the first generator element (A).

The strain and the bias voltage change non-linearly during the first relaxing step 10 and the stretching step 13. The relaxing steps 10 and 11 of the first generator element (A) take place substantially simultaneously with the stretching step 13 of the second generator element (B), and vice versa.

Fig. 5 illustrates energy transfer between generator elements of a system according to an embodiment of the invention. In the left graph the electrical energy of the first generator element (A) is at a minimum level, while the electrical energy of the second generator element (B) is at a maximum level. This is the situation occurring at $T=t_0^n$, i.e. the first generator element (A) has just completed the stretching step and is ready for being charged, and the second generator element (B) has just completed the second relaxing step, and is ready for being discharged. The harvested portion represents the energy which was discharged during the previous step.

In the right graph, the second generator element (B) has been discharged, and the first generator element (A) has been charged by transferring energy from the second generator element (B). It is also clear that some of the electrical energy which was stored on the second generator element (B) has been 'harvested', i.e. discharged to an external electrical load.

Fig. 6 is a schematic view of two generator elements 2a, 2b for use in a system according to an embodiment of the invention. The first generator element 2a comprises a first compliant electrode and a second compliant electrode arranged opposite to the first compliant electrode, thereby forming a first capacitor 3a. Similarly, the second generator element 2b comprises a first compliant electrode and a second compliant electrode arranged opposite to each other, thereby forming a second capacitor 3b.

The first generator element 2a and the second generator element 2b are mechanically interconnected via mechanical connection 15. Thereby, when the first generator element 2a is relaxed, the second generator element 2b is stretched, and vice versa.

Fig. 7 is a schematic view of two generator elements 2a, 2b for a system according to an embodiment of the invention. The first generator element 2a and the second generator element 2b are mechanically interconnected via mechanical connection 15 as described above with reference to Fig. 6. The mechanical connection 15 is further connected to a mechanical resonance system 16 comprising a mass 17 and a spring 18. Thus, mechanical energy can be transferred between each of the generator elements 2a, 2b and the mechanical resonance system 16. Thereby mechanical energy which is not converted into electrical energy during the relaxing step can be transferred to the mechanical resonance system 16. The mechanical energy may then be used for stretching one of the generator elements 2a, 2b during a subsequent stretching step. Accordingly, the mechanical energy is not 'lost', but remains in the system.

Fig. 8 shows a system 1 according to an embodiment of the invention, comprising the generator elements 2a, 2b of Fig. 7. The operation of the system 1 is substantially as described above with reference to Figs. 2-4. During the second relaxing step (11 in Fig. 4) mechanical energy is transferred to the mechanical resonance system 16 as described above with reference to Fig. 7.

Fig. 9 is a schematic view of a system according to an embodiment of the invention, the system comprising four generator elements 2a, 2b, 2c, 2n. Each of the generator elements 2 comprises a set of compliant electrodes forming a capacitor 3. A first generator element 2a is connected to the three remaining generator elements 2b, 2c, 2n via mechanical connection 15, similarly to the situation described above. It should further be understood that the generator elements 2 are electrically interconnected in such a manner that electrical energy can be transferred directly between generator elements, thereby allowing charge transfer between the generator elements 2 as described above. The electrical connections may, e.g., be such that electrical energy can be transferred from the first generator element 2a to each of the remaining generator elements, 2b, 2c, 2n, and from each of the generator elements 2b, 2c, 2n to the first generator element 2a. As an alternative, the electrical energy may be transferred between the first 2a and second 2b generator element, and between the third 2c and fourth 2n generator element, respectively. As another alternative, electrical energy may be transferred between any two of the generator elements 2.

CLAIMS

1. A system for generating electrical energy, the system comprising:

- at least two generator elements, each generator element comprising a first compliant electrode and a second compliant electrode arranged opposite to each other, thereby forming a capacitor, and each generator element being coupled to a mechanical energy input device arranged to supply mechanical energy to said generator element, and

- a charge-discharge circuit arranged to control charge and discharge of the compliant electrodes of the generator elements, said charge-discharge circuit being connected to an external electrical load,

wherein the at least two generator elements and the charge-discharge circuit are electrically interconnected in such a manner that electrical energy can be transferred directly between the generator elements, without being transferred via the external electrical load.

2. A system according to claim 1, wherein the charge-discharge circuit is arranged to transfer a portion of electrical energy stored in a generator element to the external electrical load, and to transfer at least a portion of the remaining electrical energy stored in said generator element to one or more of the other generator elements.

3. A system according to claim 2, wherein the amount of electrical energy transferred to the external load corresponds to an amount of electrical energy being converted from mechanical energy input to the generator element during a working cycle for the system.

4. A system according to any of the preceding claims, wherein the mechanical energy input device is adapted to provide forces stretching the compliant electrodes of at least one of the generator elements.

5. A system according to any of the preceding claims, wherein the mechanical energy input device is adapted to provide forces compressing the compliant electrodes of at least one of the generator elements.

6. A system according to any of the preceding claims, wherein the charge-discharge circuit comprises at least one passive electronic component arranged to control discharge of electrical energy from one or more generator elements to the external electrical load.

7. A system according to claim 6, wherein the charge-discharge circuit further comprises at least one switch arranged to control transfer of electrical energy between the generator elements.

8. A system according to claim 7, wherein the charge-discharge circuit further comprises an active electronic circuit cooperating with said switch(es) to control transfer of electrical energy between the generator elements.

9. A system according to any of the preceding claims, further comprising a mechanical resonance system being mechanically coupled to the two or more generator elements in such a manner that mechanical energy can be transferred between each of the generator elements and the mechanical resonance system.

10. A system according to claim 9, wherein the mechanical resonance system comprises at least one mass.

11. A system according to claim 9 or 10, wherein the mechanical resonance system comprises at least one spring member.

12. A system according to any of the preceding claims, wherein the compliant electrodes of at least one of the generator elements are in the form of metal layers applied to corrugated surfaces of elastomeric films.

13. A method for generating electrical energy using a system according to any of the preceding claims, the method comprising the steps of sequentially:

- decreasing the distance between the compliant electrodes of a first generator element,
- providing a charge to the compliant electrodes of the first generator element by means of the charge-discharge circuit,
- increasing the distance between the compliant electrodes of the first generator element,
- discharging a portion of the electrical energy stored in the first generator element to the external electrical load, and
- discharging at least a portion of the remaining electrical energy stored in the first generator element to one or more of the remaining generator elements of the system.

14. A method according to claim 13, wherein the step of decreasing the distance between the electrodes comprises applying a force to the compliant electrodes of the first generator element, causing the compliant electrodes to be stretched, and wherein the step of increasing the distance between the electrodes comprises allowing the electrodes to relax, thereby restoring their original size and shape.

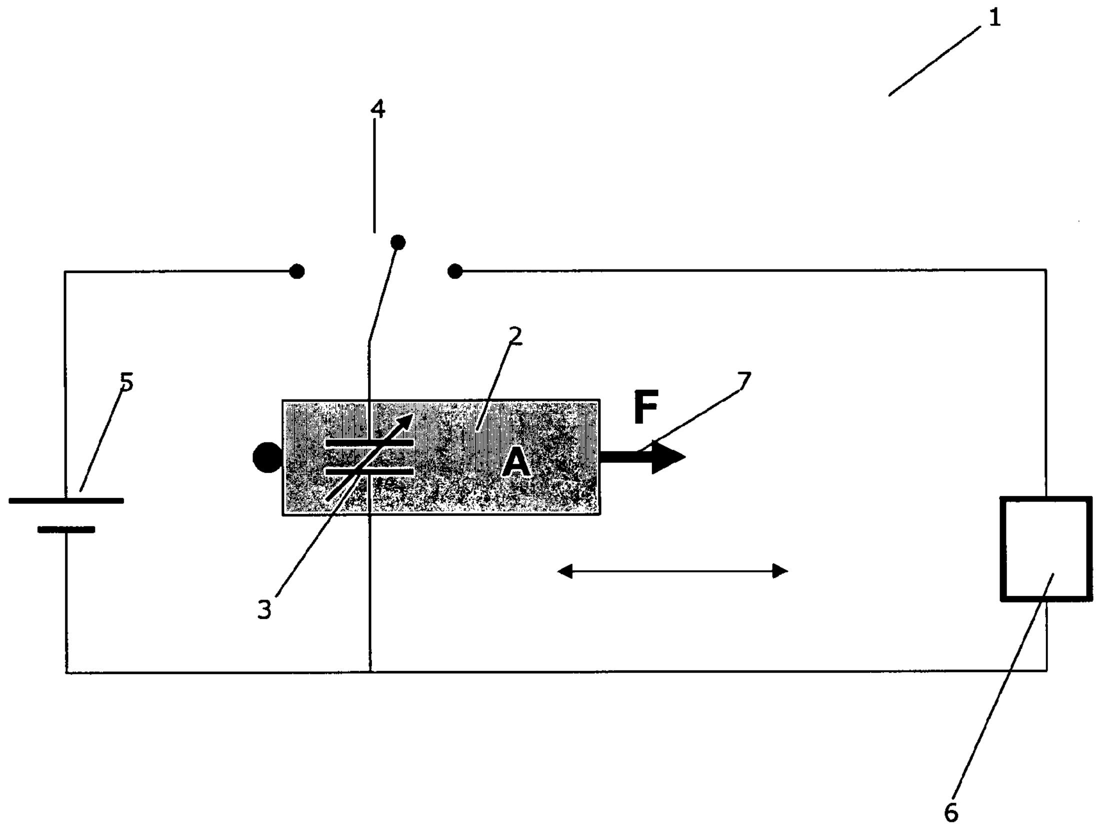
15. A method according to claim 13, wherein the step of increasing the distance between the electrodes comprises applying a force to the compliant electrodes of the first generator element, causing the compliant electrodes to be compressed, and wherein the step of decreasing the distance between the electrodes comprises allowing the electrodes to relax, thereby restoring their original size and shape.

16. A method according to any of claims 13-15, further comprising the steps of sequentially:

- decreasing the distance between the compliant electrodes of a second generator element,
- providing a charge to the compliant electrodes of the second generator element by discharging a portion of the electrical energy of the first generator element and transferring said electrical energy to the second generator element,
- increasing the distance between the compliant electrodes of the second generator element,
- discharging a portion of the electrical energy stored in the second generator element to the external electrical load, and
- discharging at least a portion of the remaining electrical energy stored in the second generator element to one or more of the remaining generator elements of the system.

17. A method according to claim 16, wherein the first generator element and the second generator element are operated in such a manner that the step of discharging at least a portion of the remaining electrical energy stored in the first generator element to one or more of the remaining generator elements and the step of providing a charge to the compliant electrodes of the second generator element are performed substantially simultaneously.

18. A method according to any of claims 13-17, further comprising the step of transferring mechanical energy to a mechanical resonance system during the step of increasing the distance between the electrodes or during the step of decreasing the distance between the electrodes.



PRIOR ART

Fig. 1

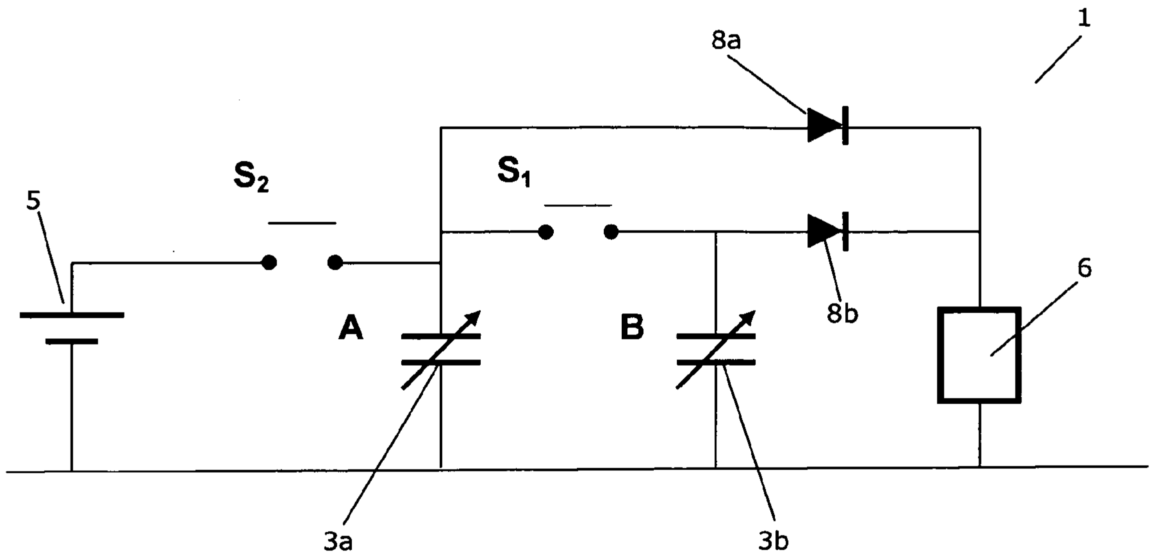

1
8a
S2
S1
5
6
8b
A
B
3a
3b

Fig. 2

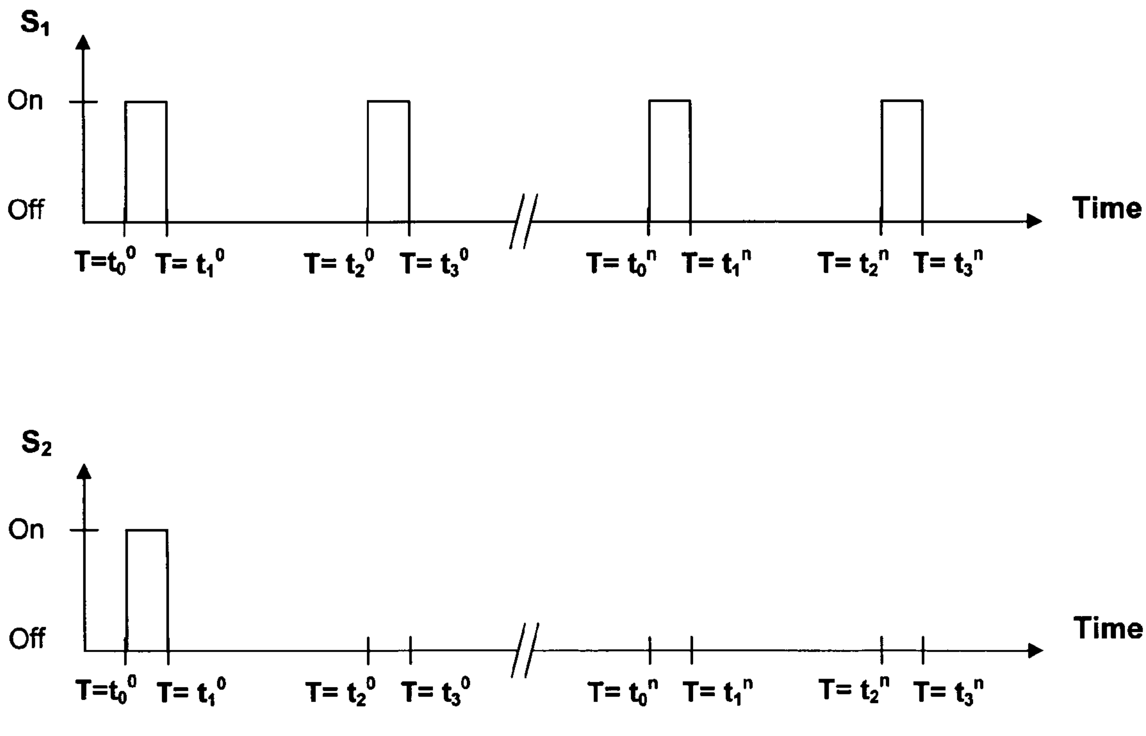

S1
On
Off
Time
T=t0 0 T= t1 0 T= t2 0 T= t3 0 T= t0 n T= t1 n T= t2 n T= t3 n
S2
On
Off
Time
T=t0 0 T= t1 0 T= t2 0 T= t3 0 T= t0 n T= t1 n T= t2 n T= t3 n

Fig. 3

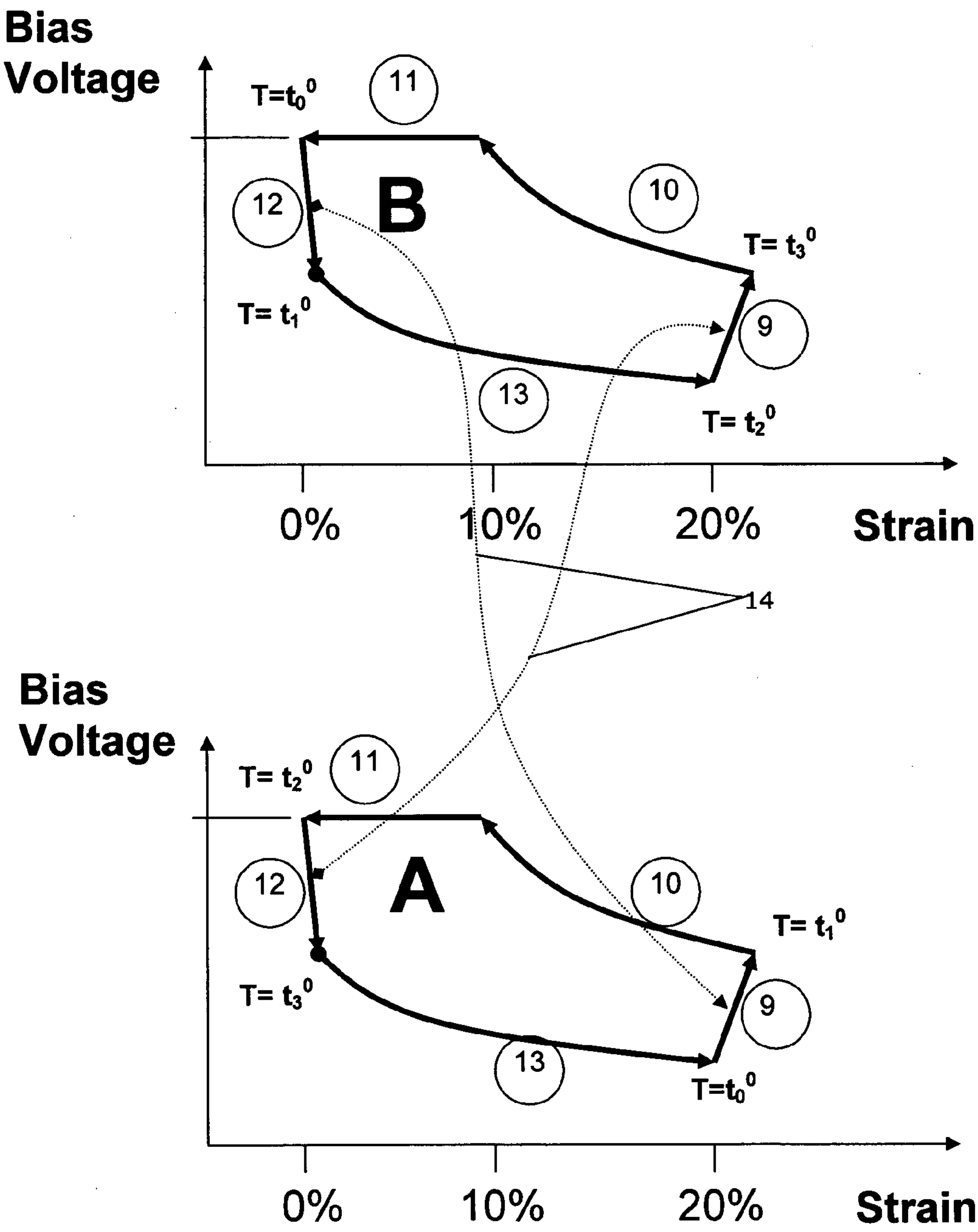

Bias Voltage
T=$t_0$⁰
11
12
B
10
T= $t_3$⁰
T= $t_1$⁰
9
13
T= $t_2$⁰
0%
10%
20%
Strain
14
Bias Voltage
T= $t_2$⁰
11
12
A
10
T= $t_1$⁰
T= $t_3$⁰
9
13
T=$t_0$⁰
0%
10%
20%
Strain

Fig. 4

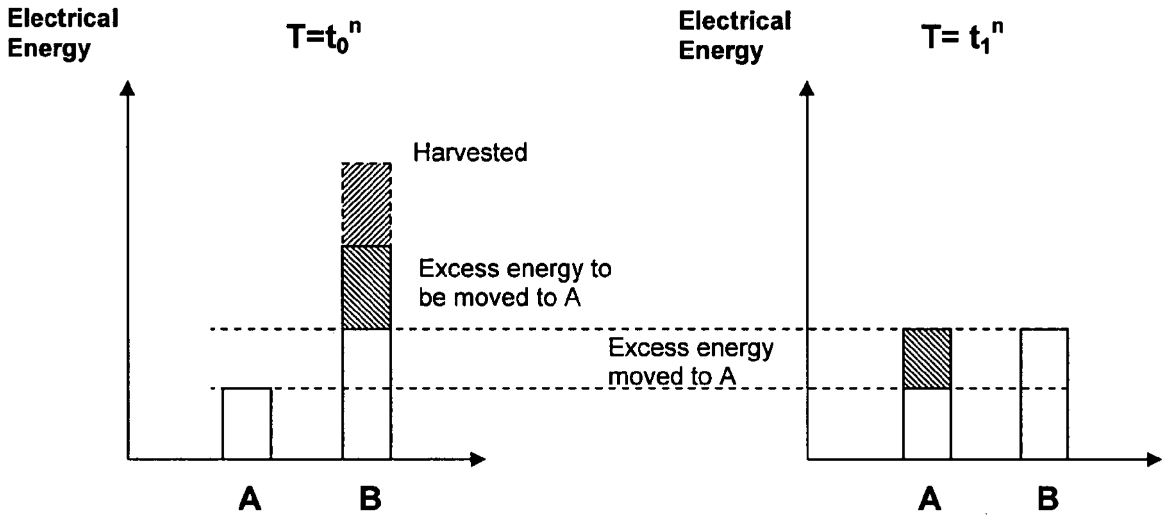

Electrical Energy
T=t0n
Harvested
Excess energy to be moved to A
Excess energy moved to A
A
B
Electrical Energy
T= t1n
A
B

Fig. 5

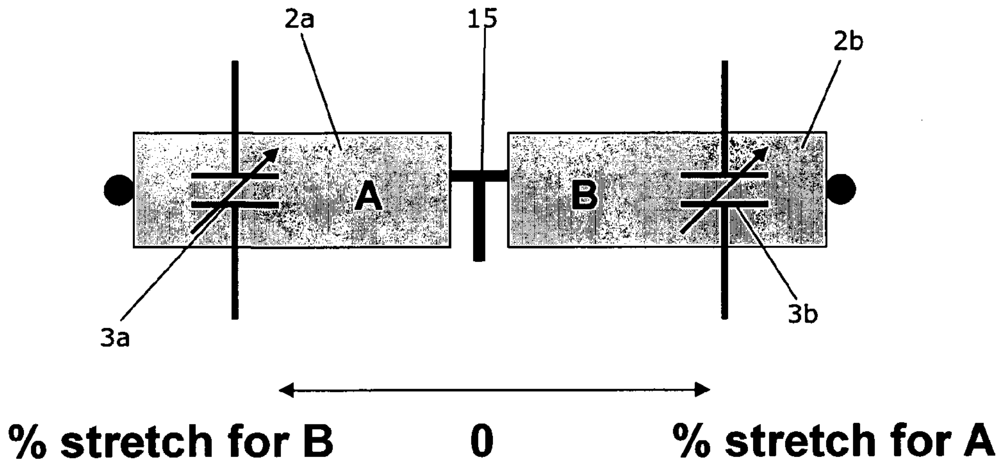

2a
15
2b
A
B
3a
3b
% stretch for B
0
% stretch for A

Fig. 6

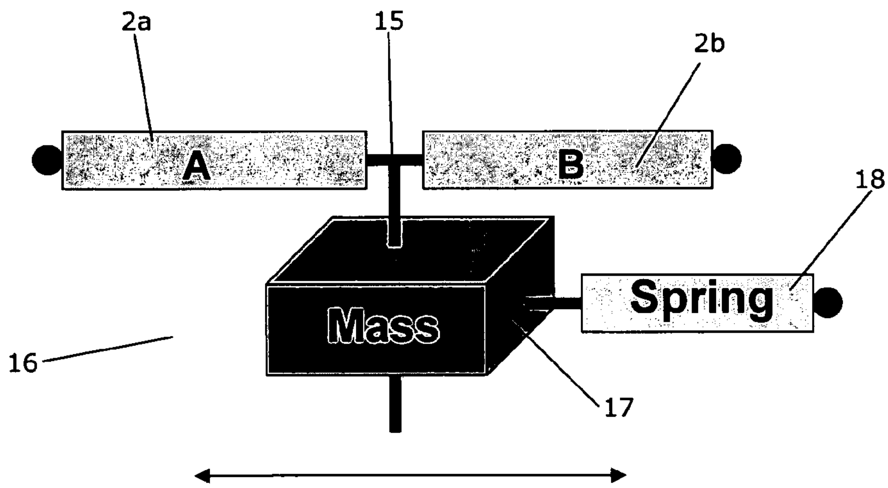

2a
15
2b
A
B
18
Spring
Mass
16
17

Fig. 7

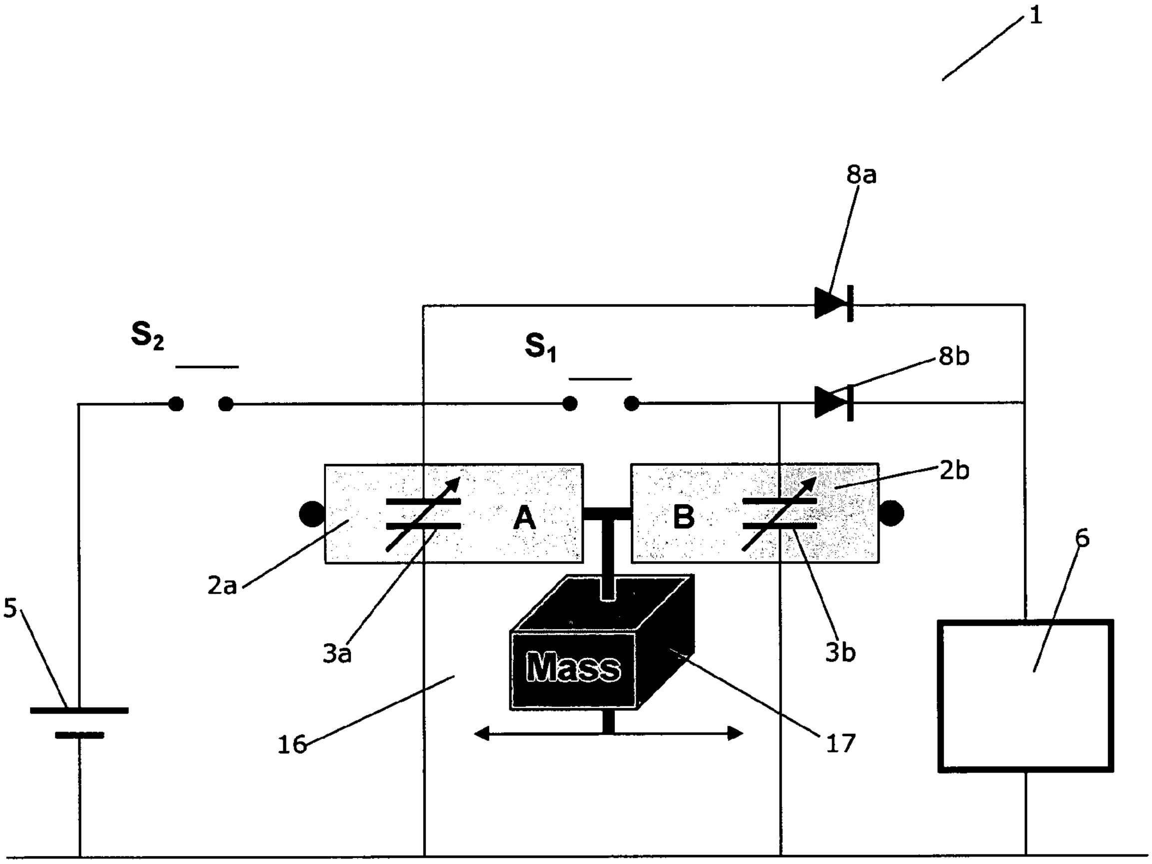


Fig. 8

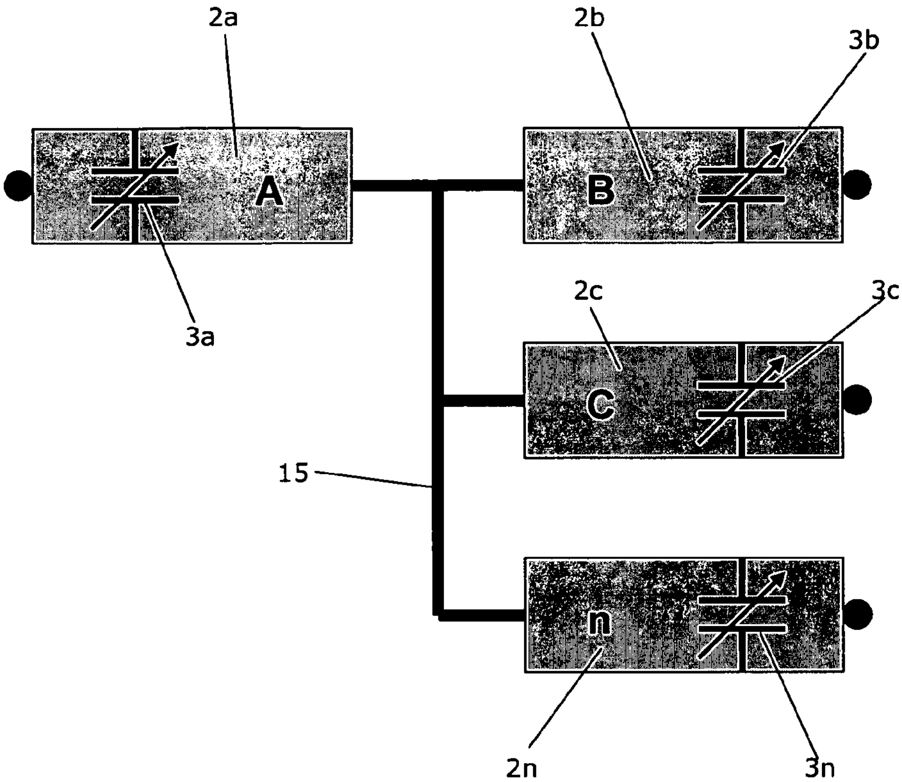


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2010/000135

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02N1/08
ADD.

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)
H01L H02N

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, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4 126 822 A (WAHLSTROM) 21 November 1978 (1978-11-21) column 6, line 53 - column 7, line 68 figure 1	1-18
Y	BAGINSKY ET AL: "The analysis of possibility of creation of the microelectronic electrostatic power generator", AVTOMETRIA, no. 1, 1 January 2002 (2002-01-01), pages 107-122, XP009143219, ISSN: 0320-7102 figure 1	1-18

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

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 January 2011	25/01/2011

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, Fax: (+31-70) 340-3016	Subke, Kai-Olaf

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	-& OSTERTAK: "Experimental evaluation of parameters of the capacitive MEMS converters", MODERN PROBLEMS OF NANOELECTRONICS, 28 October 2009 (2009-10-28), pages 97-102, XP031568237, ISBN: 978-1-4244-5534-8 page 98, column 1; figure 4	1-18
Y	DRAGUNOV ET AL: "Limit parameters of microelectromechanical energy converters", NAUÈNYJ VESTNIK NGTU, vol. 34, no. 1, 1 January 2009 (2009-01-01), pages 129-141, XP009143220, ISSN: 1814-1196 figure 2	1-18
Y	US 2006/113878 A1 (PEI ET AL) 1 June 2006 (2006-06-01) paragraphs [0058] - [0067] figure 1	1-18
Y	WO 2006/046937 A1 (MICHELIN SOC TECH) 4 May 2006 (2006-05-04) paragraphs [0037] - [0048] figures 1, 4	9-11

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/DK2010/000135

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 4126822	A	21-11-1978	NONE			
US 2006113878	A1	01-06-2006	US	2006238079	A1	26-10-2006
			US	2006113880	A1	01-06-2006
WO 2006046937	A1	04-05-2006	CN	101002343	A	18-07-2007
			EP	1803170	A1	04-07-2007
			JP	2008518573	T	29-05-2008
			US	2008129147	A1	05-06-2008