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(54) **METHOD AND DEVICE FOR DRIVING AT LEAST ONE CAPACITIVE ACTUATOR**

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**Related U.S. Patent Documents**

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(52) **U.S. Cl.** .................................................. **310/316.03**
(58) **Field of Search** .................................... 310/316.03

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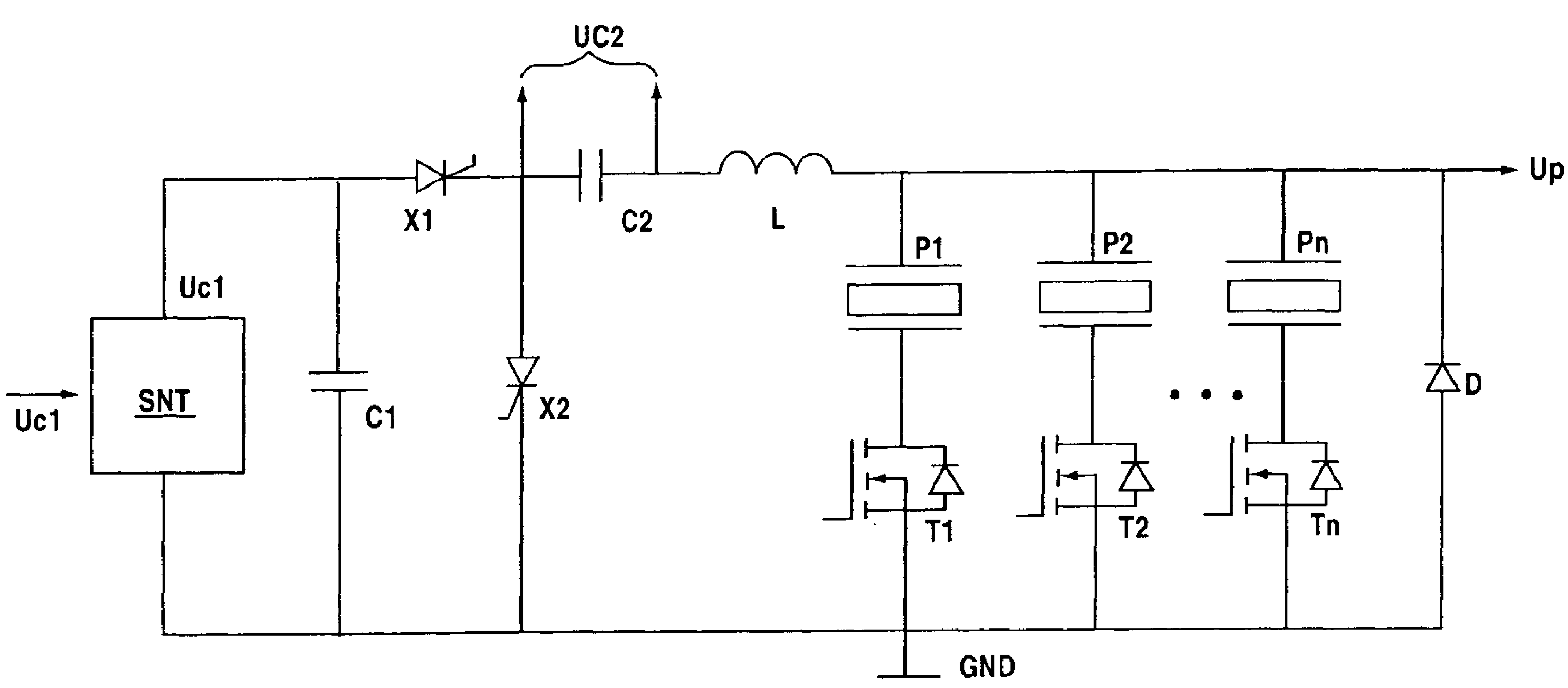
(57) **ABSTRACT**

In a driving operation, a capacitive actuator is charged from a series circuit of two capacitors having a charging voltage. An actuator voltage established at the actuator is controlled to a prescribed desired value in a course of a subsequent driving operation; the same procedure occurs for further actuators.

**8 Claims, 3 Drawing Sheets**



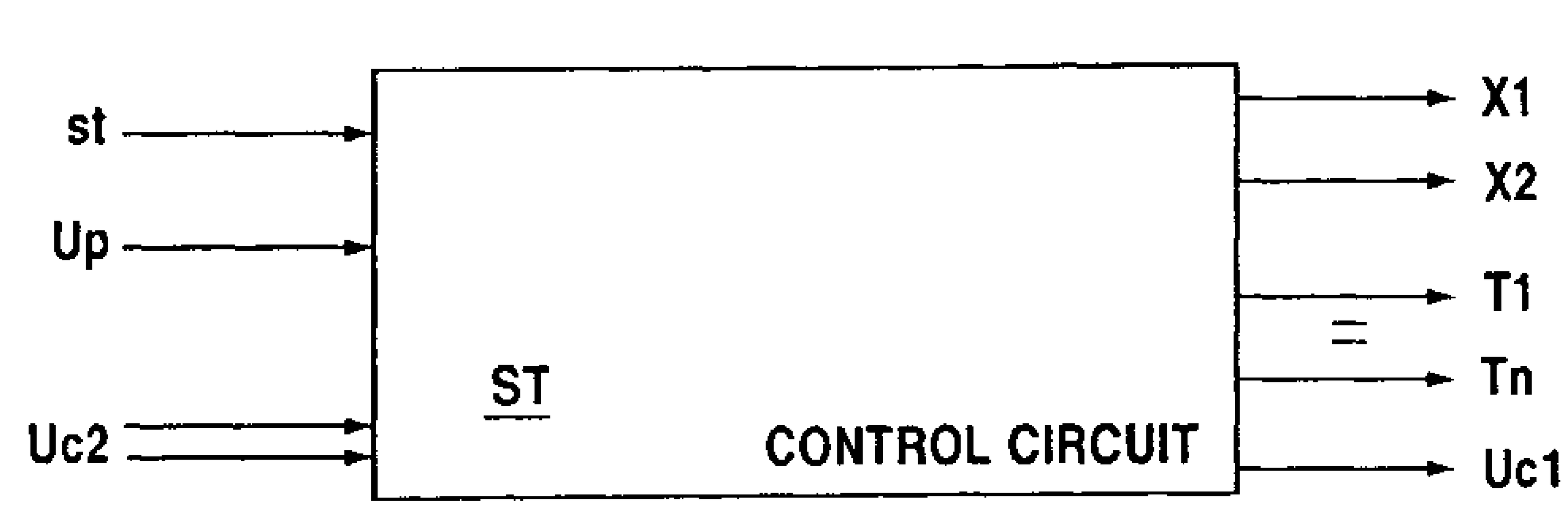



Fig.1

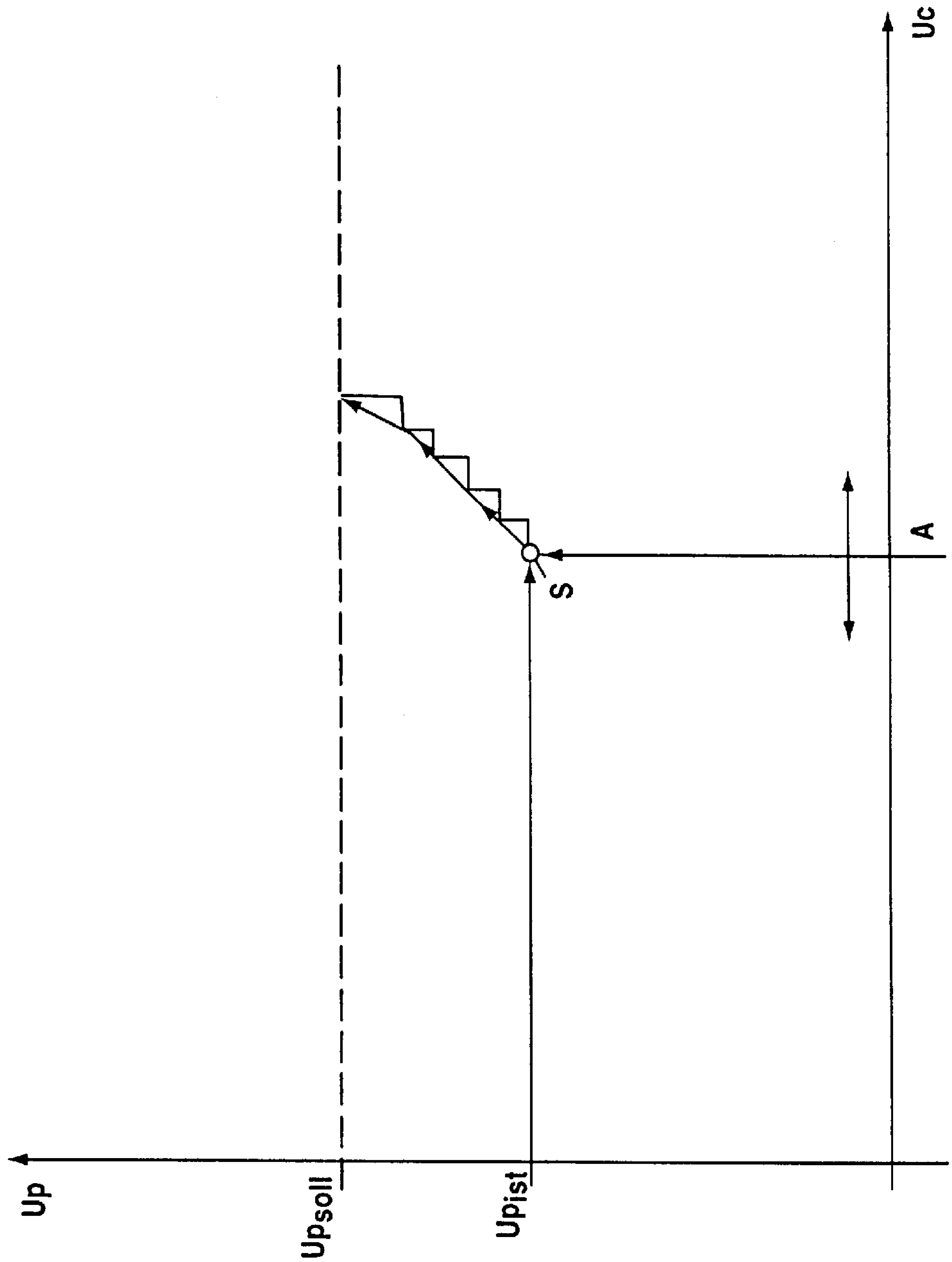


Fig.2

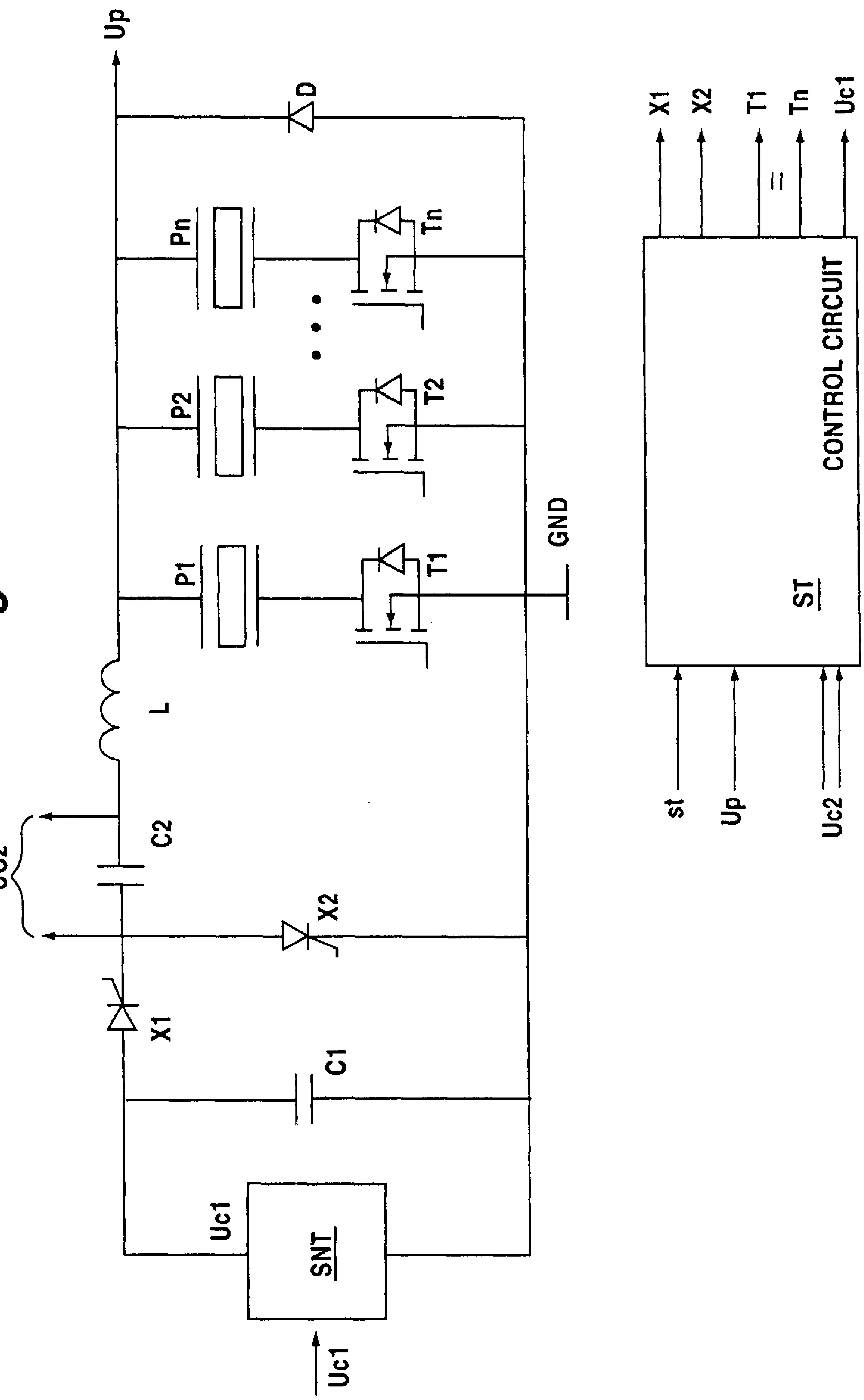
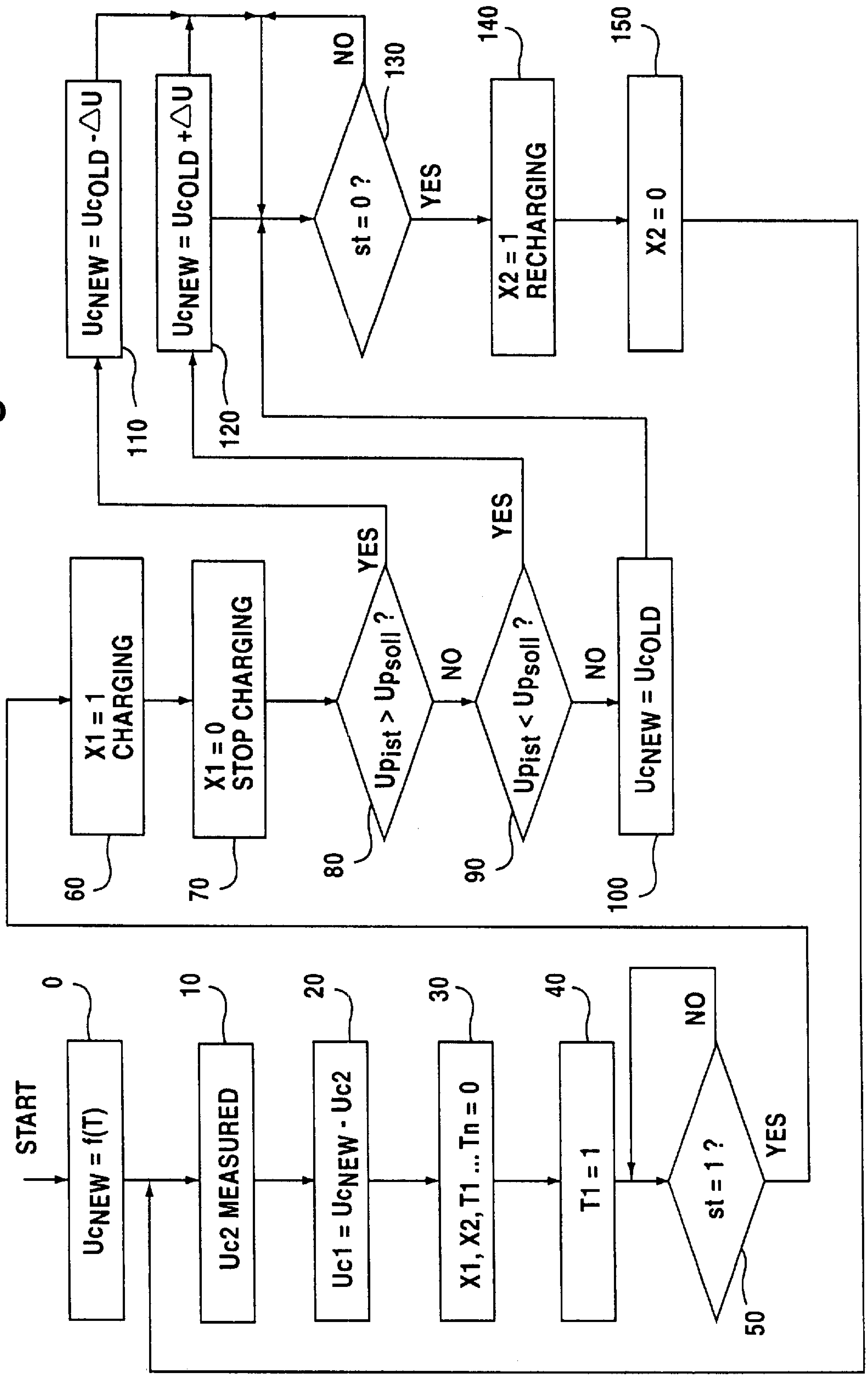

Up
D
P1
P2
Pn
T1
T2
Tn
GND
L
C2
UC2
X2
X1
C1
Uc1
SNT
Uc1
X1
X2
T1
Tn
Uc1
CONTROL CIRCUIT
ST
st
Up
Uc2

Fig.3


START
UcNEW = f(T)
0
Uc2 MEASURED
10
Uc1 = UcNEW - Uc2
20
X1, X2, T1 ... Tn = 0
30
T1 = 1
40
st = 1 ?
50
NO
YES
X1 = 1
CHARGING
60
X1 = 0
STOP CHARGING
70
Upist > Upsoll ?
80
YES
NO
Upist < Upsoll ?
90
YES
NO
UcNEW = UcOLD
100
UcNEW = UcOLD -ΔU
110
UcNEW = UcOLD +ΔU
120
st = 0 ?
130
NO
YES
X2 = 1
RECHARGING
140
X2 = 0
150

# METHOD AND DEVICE FOR DRIVING AT LEAST ONE CAPACITIVE ACTUATOR

**Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.**

## CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of copending International Application No. PCT/DE97/02905, filed Dec. 12, 1997, which designated the United States.

## BACKGROUND OF THE INVENTION

### Field of the Invention

The invention relates to a method and a device for driving at least one capacitive actuator, in particular a piezoelectrically operated fuel injection valve of an internal combustion engine.

Piezoelectric actuators contain a multiplicity of piezoceramic layers, and form a so-called stack, which upon the application of a voltage changes its dimensions, in particular its length s by a deviation ds, or generates an electric voltage in the event of a mechanical compression or tension.

Published, Non-Prosecuted German Patent Application DE 41 22 984 A1 discloses a driving device for a piezoelectric element in which the driving of the piezoelectric element is performed via corresponding electronic switches having prescribed charging and discharging times.

Published, Non-Prosecuted German Patent Application 196 32 872.1 A, corresponding to U.S. patent application Ser. No. 09/250,875, filed on Feb. 16, 1999, has already proposed a method for driving a capacitive actuator, in accordance with which the actuator is charged with a prescribed charging voltage until the voltage measured at the actuator during the driving operation reaches a prescribed value.

## SUMMARY OF THE INVENTION

It is accordingly an object of the invention to provide a method and a device for driving at least one capacitive actuator which overcomes the above-mentioned disadvantages of the prior art methods and devices of this general type, in which a method of voltage control during driving of at least one capacitive actuator is possible even when it is impossible to break off the charging operation during driving.

With the foregoing and other objects in view there is provided, in accordance with the invention, a method for driving at least one capacitive actuator, including a piezoelectrically operated fuel injection valve of an internal combustion engine, which contains:

charging, at a start of a driving operation, an actuator of a plurality of actuators with a prescribable charging voltage via a coil from a series circuit composed of a charging capacitor and a charge-reversing capacitor, and discharging the actuator into the charge-reversing capacitor at an end of the driving operation;

comparing an actuator voltage of the actuator due to the prescribable charging voltage with a prescribed desired-value voltage;

determining a new charging voltage for a next driving operation in dependence on a difference between the prescribed desired-value voltage and the actuator voltage; and



charging the charging capacitor for the next driving operation to a voltage corresponding to a difference between the new charging voltage and a voltage present across the charge-reversing capacitor.

With the foregoing and other objects in view there is further provided, in accordance with the invention, a device for driving at least one capacitive actuator, including:

a voltage source having a positive pole and a negative pole;

a charging capacitor disposed between the positive pole and the negative pole;

a control circuit controlling the voltage source;

a first series circuit disposed parallel to the charging capacitor and containing a charging switch connected to the positive pole for conducting current away from the positive pole and a discharging switch connected to the negative pole for conducting current toward the negative pole;

a ground terminal;

a second series circuit disposed between a connection point of the charging switch and the discharging switch and the ground terminal, the second series circuit containing a charge reversing capacitor having a recharge voltage connected to the charging switch and a coil;

at least one third series circuit connected in series with the second series circuit and containing an actuator having an actuator voltage and a controlled Power-MOSFET-switch; and

a diode disposed parallel to the at least one third series circuit and conducting from the ground terminal to the coil.

Other features which are considered as characteristic for the invention are set forth in the appended claims.

Although the invention is illustrated and described herein as embodied in a method and a device for driving at least one capacitive actuator, it is nevertheless not intended to be limited to the details shown, since various modifications and structural changes may be made therein without departing from the spirit of the invention and within the scope and range of equivalents of the claims.

The construction and method of operation of the invention, however, together with additional objects and advantages thereof will be best understood from the following description of specific embodiments when read in connection with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a graph of an actuator voltage Up plotted against a charging voltage Uc according to the invention;

FIG. **2** is a diagrammatic, circuit block diagram of a device for driving a plurality of actuators; and

FIG. **3** is a flowchart relating to a mode of operation of the circuit according to FIG. **2**.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention proceeds from the consideration that what is involved, as a rule, is temperature-induced variations which have a very large time constant compared with the temporal timing of successive actuator operations in an internal combustion engine, or manufacturing tolerances which do not change. There is therefore no need to carry out a control or regulation of the recharging in an actual control cycle (driving operation), it sufficing completely, instead, to determine a deviation in a driving operation and then to correct it in a subsequent driving operation.

In all the figures of the drawing, sub-features and integral parts that correspond to one another bear the same reference symbol in each case. Referring now to the figures of the drawing in detail and first, particularly, to FIG. **1** thereof, there is shown a diagram of the relationship between a charging voltage Uc and an actuator voltage Up, a prescribed actuator desired value $Up_{soll}$ being illustrated by a dashed line. The method according to the invention is described below with the aid of this diagram and of a circuit, represented in FIG. **2**, of a driving device for a plurality of capacitive actuators.

The driving of n fuel injection valves (not represented below) of an internal combustion engine via piezoelectric actuators **P1** to Pn is performed by a control circuit ST which is part of a microprocessor-controlled engine control unit.

As shown in FIG. **2**, there is connected between a positive pole and a negative pole GND of a controllable voltage source SNT, preferably of a switched-mode power supply SNT, a charging capacitor C**1**. The charging capacitor C**1** can be regarded as an output capacitor of the switched-mode power supply SNT and is charged up to an output voltage Uc**1** thereof. Disposed in parallel with the charging capacitor C**1** is a series circuit composed of a charging switch **X1**, which is connected to the positive pole and passes current away from it, and a discharging switch **X2**, which is connected to the negative pole GND and passes current toward it.

The switches **X1** and **X2** are electronic switches, preferably thyristor switches, which pass current only in one direction, contain at least one semiconductor element and are turned on by the control circuit ST.

Situated between the connection point of the charging switch **X1** and the discharging switch **X2** and a frame terminal GND is a series circuit composed of a charge-reversing capacitor C**2**, a ring-around coil L, a first actuator **P1** and a first, controlled power MOSFET switch T**1**.

For each further actuator, a series circuit composed of an actuator **P2** to Pn and a further power MOSFET switch T**2** to Tn is connected in parallel with the series circuit composed of the first actuator **P1** and the first power MOSFET switch T**1**.

Disposed in parallel with the series circuits composed of the actuator **P1**–Pn and the power MOSFET switch T**1**–Tn is a diode D which passes current away from the frame terminal GND toward the ring-around coil L. Power MOSFET switches usually include inverse diodes whose function, as explained in more detail further below, are employed in operating the device according to the invention.

The switches **X1**, **X2** and T**1** to Tn are controlled by the control circuit ST in accordance with a program, assigned to the method according to the invention, as a function of control signals st of the engine control unit, of the actuator voltage Up and of a voltage Uc**2** present across the charge-reversing capacitor C**2** after discharging of the actuator **P1**–Pn.

The method according to the invention for successively driving the plurality of capacitive actuators **P1**–Pn is explained in more detail below for the actuator **P1** with the aid of the flowchart represented in FIG. **3** on the basis of the circuit shown in FIG. **2**. The individual boxes, assigned to the respective method states, are marked by reference numerals.

The charging voltage Uc (=Uc**1**+Uc**2**) is prescribed an initial value A (state **0**) in the first driving operation when the vehicle is started. The value of the charging voltage Uc can be a function of an engine temperature: Uc=f(T), since the actuator capacitance can vary by a factor 2 in the engine temperature range.

In the case of a first driving operation, the charge-reversing capacitor C**2** is discharged, Uc**2**=0V (state **10**). Consequently, the output voltage of the controllable voltage source SNT is set to the voltage Uc**1**=Uc (initial value A) (state **20**).

In a state **30**, in which the ring-around coil L is deenergized, all of the switches **X1**, **X2** and T**1** to Tn are turned off (of high resistance), and all the actuators **P1** to Pn are discharged. The aim is to operate the actuator **P1** in order to inject fuel into the cylinder via the assigned injection valve. Firstly, the control circuit directs the corresponding actuator **P1**, for example, (state **40**) by turning on the power MOSFET switch T**1** assigned to it. T**1** can remain turned on (of low resistance) via a crank shaft angle KW=720° KW/Z (Z=number of cylinders), that is to say, for example, 180° KW for four-cylinder engines and 120° KW for six-cylinder engines.

At the start of injection, which is prescribed by the control signal st=1 (state **50**), the charging switch **X1** is triggered by the control circuit ST (state **60**). Consequently, the charging voltage Uc present on the series circuit composed of the capacitors C**1** and C**2** is discharged during a completely sinusoidal half oscillation via the ring-around coil L into the actuator **P1**, and the latter opens the non-illustrated injection valve. The voltage source, i.e. the switched-mode power supply SNT, remains connected to the charging capacitor C**1**, with the result that it also feeds energy into the resonant circuit.

After the charging process, the charging switch **X1** is automatically switched off (state **70**), and the actuator **P1** is charged to an actuator voltage $Up_{ist}$. The result in FIG. **1** is a point of intersection S of the charging voltage Uc and the actuator voltage $Up_{ist}$.

The actual value of the actuator voltage $Up_{ist}$, established at the actuator **P1** at an end of the charging cycle, is communicated to the control circuit ST which compares it with a prescribed desired value $Up_{soll}$ illustrated by the dashed line in FIG. **1** (states **80** and **90**).

If the actual value $Up_{ist}$ is greater than the desired value $Up_{soll}$ (state **80**), a new value is determined for the charging voltage Uc: $Uc_{new}=Uc_{old}$-DU (state **110**) is determined for the next driving operation of the actuator **P1**. A lower actuator voltage $Up_{ist}$ is then set thereupon in the next driving operation. If the actual value $Up_{ist}$ is, however, less than the desired value $Up_{soll}$ (state **90**), a larger, new value for the charging voltage Uc: $Uc_{new}=Uc_{old}$+DU (state **120**) is determined for the next driving operation. If the value $Up_{ist}$ is equal to the desired value $Up_{soll}$ (state **100**), the charging voltage Uc remains unchanged at the next driving operation of the actuator **P1**. As described and indicated by arrows in FIG. **1**, the process of approximation to the desired value can be performed incrementally by prescribed steps DU, or according to any desired process of approximation.

The discharging switch **X2** is fired (state **140**) in order to discharge the actuator **P1** at the end (removal) of the control signal st (state **130**). The discharging circuit is closed via the inverse diode of the power MOSFET switch T**1**. The energy stored in the actuator P conducts back via the ring-around coil L into the charge-reversing capacitor C**2**; the energy stored in it can be used for the next driving operation.

As soon as the actuator **P1** is discharged to the threshold voltage of the diode D connected in parallel to the "active" channel, the current still flowing is continued via the diode, thereby preventing the actuator **P1** from being charged to a negative voltage. The discharging switch **X2** is subsequently automatically switched off (state **150**).

For the next driving operation of the actuator **P1**, the charging capacitor **C1** must be recharged to a voltage $Uc1=Uc-Uc2$, for which purpose $Uc2$ is measured (state **10**). It is thereby possible to determine $Uc1=Uc-Uc2$ (state **20**). The switched-mode power supply SNT is set to this value for the next driving operation of the actuator **P1**, and the charging capacitor **C1** is thereby charged to $Uc1$. The values determined in this driving operation are used to carry out the next driving operation, from state **30**. The driving operations for the other actuators **P2** to Pn correspond to the method described for the actuator **P1**.

We claim:

**1**. A method for driving at least one capacitive actuator, including a piezoelectrically operated fuel injection valve of an internal combustion engine, which comprises:

charging, at a start of a driving operation, an actuator of a plurality of actuators with a prescribable charging voltage via a coil from a series circuit composed of a charging capacitor and a charge-reversing capacitor, and discharging the actuator into the charge-reversing capacitor at an end of the driving operation;

comparing an actuator voltage of the actuator due to the prescribable charging voltage with a prescribed desired-value voltage;

determining a new charging voltage for a next driving operation in dependence on a difference between the prescribed desired-value voltage and the actuator voltage; and

charging the charging capacitor for the next driving operation to a voltage corresponding to a difference between the new charging voltage and a voltage present across the charge-reversing capacitor.

**2**. The method according to claim **1**, which comprises setting at a start of the driving operation a prescribed value for the prescribable charging voltage for each of the plurality of actuators.

**3**. The method according to claim **2**, which comprises setting the prescribed value for the prescribable charging voltage in dependence on an engine temperature.

**4**. A device for driving at least one capacitive actuator, comprising:

a voltage source having a positive pole and a negative pole;

a charging capacitor disposed between said positive pole and said negative pole;

a control circuit controlling said voltage source;

a first series circuit disposed parallel to said charging capacitor and containing a charging switch connected to said positive pole for conducting current away from said positive pole and a discharging switch connected to said negative pole for conducting current toward said negative pole;

a ground terminal;

a second series circuit disposed between a connection point of said charging switch and said discharging switch and said ground terminal, said second series circuit containing a charge reversing capacitor having a recharge voltage connected to said charging switch and a coil;

at least one third series circuit connected in series with said second series circuit and containing an actuator having an actuator voltage and a controlled Power-MOSFET-switch; and

a diode disposed parallel to said at least one third series circuit and conducting from said ground terminal to said coil.

**5**. The device according to claim **4**, wherein said voltage source is a switched-mode power supply.

**6**. The device according to claim **4**, wherein said control circuit is a part of a microprocessor-controlled engine control unit, said control circuit being fed as input variables control signals for driving said actuator, said actuator voltage present at a respectively driven actuator and said recharge voltage present across said charge-reversing capacitor, said control circuit further controlling said charging switch, said discharging switch and said Power-MOSFET-switch for charging and discharging said actuator.

**7**. The device according to claim **4**, wherein said charging switch and said discharging switch are electronic semiconductor switches passing current only in one direction.

**8**. The device according to claim **4**, wherein said at least one third series circuit is a plurality of third series circuits disposed parallel to each other and all in series with said second series circuit.

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