

RAPID CHARGER FOR ULTRACAPACITORS

FIELD OF THE INVENTION

5 [01] The present invention relates generally to energy storage systems. More particularly, the invention relates to methods and systems for charging energy storage systems that incorporate ultracapacitors.

BACKGROUND

10 [02] The following description is provided to assist the understanding of the reader. None of the information provided or references cited is admitted to be prior art to the present invention.

[03] Ultracapacitors can be an excellent source of energy in many applications. They offer several advantages over other types of energy storage systems such as batteries. For example, once depleted, ultracapacitors can be recharged at a significantly faster rate than batteries. Under ideal conditions, the recharge rate can be as high as the discharge rate.

15 [04] Existing recharges for ultracapacitors generally provide a constant current into the ultracapacitor to provide recharging energy. Although this provides a constant recharge rate, the rate is limited by the output current of the recharging energy source. For example, an energy source for recharging may be a 50-volt, 20-ampere, direct current source. The recharging current is limited to the 20-ampere current from the source.

20 [05] Thus, the time to recharge the ultracapacitor to 100% of capacity is dictated by the output current level of the source. In many circumstances, it would be desirable to achieve a recharge rate greater than that achieved at the current level of the energy source.

SUMMARY OF THE INVENTION

25 [06] The disclosed embodiments of the present invention provide systems and methods for recharging an ultracapacitor at a faster rate than allowed by the constant-current configuration described above. Thus, faster recharging of a depleted ultracapacitor can be achieved.

[07] In one aspect, the invention provides an arrangement for charging a power module. The arrangement includes a power module comprised of one or more ultracapacitors and an energy
30 source connected to the power module. A positive terminal of the energy source is connected to a positive terminal of the power module, and a negative terminal of the energy source is connected to

a negative terminal of the power module. A control circuit is adapted to maintain a constant power level at the power module as the voltage level across the power module increases.

[08] A "power module" may be a bank of ultracapacitors, such as twenty-two 2700-farad ultracapacitors connected in series. The power module may be implemented as a rack-mountable package containing the bank of ultracapacitors.

[09] "Ultracapacitors" are well-known to those skilled in the art. Ultracapacitors are also known as double-layer capacitors and supercapacitors, but will be referred to herein as ultracapacitors. Ultracapacitors generally include two current collecting plates, each having a corresponding electrode and being separated by a separator. Energy is stored in the form of a charge at the separated electrodes. For more detail on ultracapacitors, reference may be made to U.S. Patent Nos. 5,621,607, 5,777,428, 5,862,035, 5,907,472, 6,059,847, 6,094,788 and 6,233,135, each of which is hereby incorporated by reference in its entirety.

[10] In one embodiment, the control circuit includes a pulse-width modulator and an inductor connected in series with the power module. The pulse-width modulator can control a charge level of the inductor. The charge level may correspond to a current level which is in accordance with a desired power level at the power module and an instantaneous voltage level across the power module. The pulse-width modulator may be adapted to limit a current level through the power module to a predetermined peak level.

[11] In one embodiment, the control circuit is adapted to provide a current level through the power module greater than a current level from said energy source during at least a portion of a charging period.

[12] In another aspect, the invention provides a constant-power charging circuit for an ultracapacitor power module. The circuit includes a pulse-width modulator and an inductor connected in series with the pulse-width modulator the said power module. The pulse-width modulator is adapted to control the charge level of the inductor.

[13] In another aspect, the invention includes a method of charging an ultracapacitor power module. The method includes charging an inductor connected in series between an energy source and the power module. The charge level of the inductor is controlled to achieve a desired current level through the power module.

[14] In one embodiment, control step includes modulating the current from the energy source to the inductor through a pulse-width modulator.

[15] The desired current level may correspond to a desired power level at the power module. The power level may be constant during charging of the power module.

In one embodiment, an arrangement for charging a power module comprises: a power module including one or more capacitors; an energy source; and a control circuit coupled to the power module and to the energy source to provide a higher current level to said power module than output by said energy source for at least a portion of a charging period. The control circuit may be adapted to maintain a constant power level at the power module as the voltage level across the power module increases. The control circuit may include a pulse-width modulator and an inductor connected in series with said power module. The pulse-width modulator may control a charge level of said inductor. The charge level may correspond to a current level which is in accordance with a desired power level at said power module and an instantaneous voltage level across said power module. The inductor may be adapted to limit a current level through said power module to a predetermined peak level. The control circuit may be adapted to provide a current level through said power module greater than a current level from said energy source during at least a portion of a charging period. The one or more capacitor may comprise an ultracapacitors. The one or more capacitor may comprise a value greater than about 1 Farad.

In one embodiment, a constant-power charging circuit for an ultracapacitor power module comprises: a pulse-width modulator; and an inductor connected in series with said pulse-width modulator and said power module; wherein said pulse-width modulator is adapted to control the charge level of said inductor. The charge level may correspond to a current level which is in accordance with a desired power level at said power module and an instantaneous voltage level across said power module. The inductor may be adapted to limit a current level through said power module to a predetermined peak level. The control circuit may be adapted to provide a current level through said power module greater than a current level from said energy source during at least a portion of a charging period.

In one embodiment, a method of charging a capacitor power module comprises charging an inductor connected in series between an energy source and said power module; and controlling a charge level of said inductor to achieve a desired current level through said power module. The controlling may include modulating the current from said energy source to said inductor through a pulse-width modulator. The desired current level may correspond to a desired power level at said power module. The power level may be constant during charging of said power module. The desired current level through said power module may be greater than a current level from said energy source during at least a portion of a charging period.

In one embodiment, a constant power charge module comprises a power module including one or more capacitors; an energy source; a voltage sense circuit, the voltage sense circuit adapted

to sense a voltage of the energy source and to output a signal when the voltage is sensed; and a control circuit adapted to provide a higher current level to said power module than output by said energy source for at least a portion of a charging period of the constant power charge module and the signal. The one or more capacitors may comprise a capacitance of about 1 Farad or more.

5 In one embodiment, a constant power charge module comprises: one or more capacitor; energy source means for providing a signal; and control circuit means for provide a higher current level to the capacitor than output by said energy source for a least a portion of a charging period of the constant power charge module and the signal.

10 In one embodiment, a method for charging a capacitor comprises the steps of: providing an energy source for charging the capacitor over a charging period; and providing a higher current to the capacitor than output by the energy source for at least a portion of the charging period.

In one embodiment, a regenerative apparatus comprises: one or more capacitors; an energy source; a voltage sense circuit, the voltage sense circuit adapted to sense a voltage of the energy source and to output a signal when the voltage is sensed; and a control circuit adapted to provide a higher current level to said one or more capacitor than output by said energy source for at least a portion of a charging period of the one or more capacitors and the signal. The capacitors may comprise ultracapacitors. The energy source may comprise a regenerative braking motor. The braking motor may comprise a hybrid vehicle braking motor.

15 [16] While benefits, aspects, and embodiments of the present invention are described herein, it should be understood that such descriptions are exemplary of uses and aspects of the presently described charging systems and methods and should not be limiting in content.

DESCRIPTION OF DRAWINGS

[17] Figure 1A is a schematic illustration of a prior-art, constant-current charging circuit;

25 [18] Figure 1B is a chart illustrating the charge profile for an ultracapacitor power module using the charging circuit of Figure 1A;

[19] Figure 2A is a schematic illustration of an embodiment of a constant-power charging circuit according to the present invention;

[20] Figure 2B is a chart illustrating the charge profile for an ultracapacitor power module using the charging circuit of Figure 2A; and

30 [21] Figure 3 illustrates, in detail, one embodiment of a constant-power charging circuit illustrated in Figure 2A.

[22] Figure 4 illustrates an embodiment wherein a fuel cell is provided as an energy source.

DETAILED DESCRIPTION

[23] The present invention is generally directed to rapid charging systems and methods for recharging ultracapacitor power modules. In this regard, the present invention allows the rapid charging of ultracapacitors, thereby significantly reducing the time required for recharging, for example, a bank of ultracapacitors or other storage devices. In one embodiment of the invention, a system and method for charging charge storage devices at a higher current than a source current allows that recharging time is reduced.

[24] Although ultracapacitors are described further herein in embodiments, it is understood that the scope of the present invention extends to other types of storage devices, for example, conventional capacitors and rechargeable batteries. Ultracapacitors are well known to those skilled in the art as an efficient energy storage system. Ultracapacitors are typically provided with values of about 1 Farad and above. Ultracapacitor power modules can include a bank of ultracapacitors connected in series to provide a desired voltage level for the particular application. One attractive feature of ultracapacitors (and capacitors in general) as an energy source is their ability to be recharged in a relatively short period of time once the ultracapacitors are completely or partially depleted. Ultracapacitors are capable of providing a large capacitance in a small form factor, for example, about 500 Farads can be provided by a D-Cell sized capacitor. Those skilled in the art will identify that as compared, for example, to electrolytic capacitors that are capable of capacitances with micro-farad values, the time needed to fully charge an ultracapacitor would be greater. One or more of the embodiments of the present invention described herein allow that more rapid charging of capacitors may be achieved, which when used with large capacitance capacitors such as ultracapacitors can result in an appreciable decrease in charging time.

[25] The recharge rate of a capacitor, an ultracapacitor or a bank of ultracapacitors in a power module can be described by the following equation:

$$dV/dt = I / C ,$$

where dV/dt is the rate of increase of voltage in the ultracapacitor, I is the current through the ultracapacitor, and C is the capacitance of the ultracapacitor.

[26] As described above, present charging circuits use a constant current configuration, as illustrated schematically in Figure 1A. In this arrangement, an energy source 102 is provided for recharging a power module 104. In this regard, the positive terminal of the source 102 is connected

to the positive terminal of the power module 104, and the negative terminal of the source 102 is connected to the negative terminal of the power module 104.

[27] A constant-current circuit 106 is provided to regulate the current being supplied to the power module 104. In this regard, the power module 104 receives a constant current, typically equal to the output current of the source 102. Referring to the equation above, with a constant current, I , and a constant capacitance of the power module 104, it is apparent that the charge rate, dV/dt is also constant. An exemplary charge profile for this arrangement is illustrated in Figure 1B.

[28] In order to improve the charge rate, the current through the power module should be increased. According to one embodiment of the present invention, a circuit to provide a constant power to the power module achieves this goal. Figures 2A and 2B illustrate one such embodiment. The arrangement 200 includes an energy source 202 for recharging an ultracapacitor power module 204. The positive terminal of the energy source 202 is connected to the positive terminal of the power module 204, and the negative terminal of the energy source 202 is connected to the negative terminal of the power module 204.

[29] The energy source 202 may be, for example, a fuel cell, a battery or other power source. In one embodiment, the energy source 202 includes an AC power grid with a DC converter to provide direct current. In the illustrated embodiment, the energy source 202 is a 20-ampere, 50-volt power source. It will be understood by those skilled in the art that the size of the energy source may vary according to requirements.

[30] The ultracapacitor power module 204 may be a single ultracapacitor or a bank of ultracapacitors connected in series, for example. In one embodiment, the power module includes a bank of twenty-two 2700-farad ultracapacitors connected in series. The power module 204 typically has a rated voltage when the power module 204 is fully charged.

[31] A constant-power circuit 206 provides a constant power to the power module 204. As is well known to those skilled in the art, power is the product of current and voltage. Thus, when the power module 204 is substantially depleted (i.e., has a low voltage), the current level is relatively high if the power is constant. Thus, as illustrated in Figure 2B, at the lower voltage area, the constant-power charging provides a significantly more rapid recharging than the constant-current charging.

[32] Figure 3 provides a schematic illustration of one embodiment of a constant-power charging circuit 206. In this embodiment, the charging circuit 206 includes a current measuring device 208, for example, a Hall effect device, which provides an input to a pulse-width modulator 210. Current measuring or detection devices 208 are well-known to those skilled in the art, as are pulse-width modulators, which are also known as pulse-duration modulators. The pulse-width modulator 210

actuates a switch 212 through which the pulse-width modulator allows pulses of current to pass. The width of the pulses can be modulated to provide a current profile associated with a desired power level for the power module.

5 [33] A capacitor 218 is provided across the input from the source 202. The capacitor 218 is preferably capable of storing a small amount of energy, and should be sized to achieve the desired output result. The capacitor 218 serves to protect the source 202 from experiencing fluctuations during operation of the pulse-width modulator 210.

10 [34] An inductor 216 is provided in series with the power module 204. Preferably, the inductor is sized to minimize the voltage dissipated. The inductor 216 serves to provide an average current through the power module 204 while the pulse-width modulator 210 is operating, as described below.

[35] In operation, the inductor 216 is first charged to a current level associated with the instantaneous voltage level across the power module 204 and the desired constant-power level. For example, if the present voltage across the power module 204 is 40 volts and the desired constant-power level is 1000 watts, the inductor 216 is charged to a peak current of 25 amperes.

15 [36] In many cases, the initial voltage across the power module 204 may be very low or zero. In this case, the constant-power level dictates an extremely high peak current level. Such a level may be dangerous to certain components in the system. To protect such components, the peak current level may be limited to a pre-selected level, such as 50 amperes. Thus, for a constant-power level of 1000 watts, the inductor may be charged to a level of 50 amperes until the voltage across the power
20 module 204 reaches 20 volts.

[37] The pulse-width modulator 210 opens and closes the switch 212 to control the charge level of the inductor 216 and, therefore, control the current level through the power module 204. When the switch 212 is closed, energy from the source 202 is directed to the inductor 216, thereby charging the inductor 216. When the switch 212 is open, the current in inductor 216 flows through diode 214
25 to continue to provide charge current to the power module 204.

[38] The operation of the pulse-width modulator 210 thus provides a peak current level that may be limited to, for example, 50 amperes in the illustrated example. Depletion of energy from the inductor allows a peak current greater than the source current.

30 [39] As the voltage level across the power module 204 increases, the pulse-width modulator 210 can reduce the current level through the power module 204 by decreasing the charge level of the inductor 216.

[40] Thus, at the start of the charging, the inductor may be provided with a high current-level charge. The high level may be maintained by the pulse-width modulator by providing energy from

the source 202. As the voltage level across the power module 204 increases, a lower current level through the power module 204 is desired. To this effect, the pulse-width modulator 210 provides constant energy from the source 202 to the inductor 216, causing the current level of the inductor to decrease as the power module voltage increases.

5 [41] The ratio of capacitor charging voltage to the source voltage sets the duty cycle for the pulse-width modulator. The result is increased charge current into the power module 204 and reduced charging time. For example, if the source is 50V and the voltage across the power module 204 is 25V, the pulse-width modulator operates at a 50%-duty cycle. In this example, the inductor will charge to 40A for 50% of the time to draw 20A from the source. The 40A will flow into the power
10 module 204.

[42] The current profile resulting from the operation of the pulse-width modulator 210 is a series of current pulses. In one embodiment, the pulse-width modulator 210 operates at a frequency of 50 KHz. Thus, the pulses of current are between zero and 20 microseconds in duration. The overall average from the pulses is equal to the current from the source, or 20 amperes in the illustrated
15 example. The current at the outset may be substantially greater than the source current, while the later current may be substantially lower when the voltage across the power module is relatively high.

A diode 214 is provided across the power module 204. The diode 214 provides a current path for the inductor current to continue to flow when switch 212 is open.

[43] It will be understood by those skilled in the art that, although the preferred embodiment
20 employs a constant-power charging profile, other embodiments may not include such a profile. For example, some embodiments may provide a current at the earlier stages of recharging that is at a higher level than the source current. The current level may drop in the later stages, but without maintaining a constant-power profile.

[44] Figure 4 illustrates an embodiment, wherein a fuel cell is provided as an energy source. In
25 some embodiments, it may be necessary to operate with an energy source 202 that does not have a full current capability, for example, the full current demand of a constant power charging circuit 211. During an energy source 202 power up cycle to full power, the current demand of the charging circuit may load the energy source 202 to cause it to output a lower than normal output voltage. In some
embodiments, for example, wherein fuel cells are used as an energy source 202, during a power up
30 cycle, the fuel cells may become loaded to cause them to fall below some minimum output voltage. If a fuel cell becomes loaded such that it outputs a voltage below some minimum voltage, its normal operation may be negatively impacted.

[45] To safeguard against undesirable loading of an energy source 202, one embodiment of a constant-power charging circuit 211 includes a voltage sense circuit 213. In one embodiment, voltage sense circuit 213 comprises an under voltage circuit that utilizes a voltage comparator. Voltage sense circuit 213 may be configured to reduce the charge current provided to an
5 ultracapacitor power module 204 until the output voltage of an energy source 202 is above some minimum threshold voltage. In one embodiment, voltage sense circuit 213 is configured to detect an output voltage of the energy source 202, and based on the output voltage to cause a change in operation of the pulse-width modulator 210. In one embodiment, a duty cycle of the modulator 210 is altered based on detection of the output voltage of the energy source 202. In one embodiment, a
10 charge current provided to ultracapacitor power module 204 is reduced by altering the duty cycle of the modulator 210 until energy source 202 achieves some threshold voltage, at which point the constant-power charging circuit 211 resumes operation as described previously above.

[46] It is identified that the present invention would find utility in regenerative type applications. For example, it is known that hybrid vehicles utilize back EMF generated by a motor and/or generator
15 interconnected to wheels of a vehicle. Rotational motion of the wheels can be thus be used to re/charge one or more capacitors or batteries during braking in a faster manner than previously possible.

Thus, while the particular systems and methods herein shown and described in detail are fully capable of attaining the above described object of this invention, it is understood that the
20 description and drawings presented herein represent some, but not all, embodiments of the invention and are therefore representative of the subject matter which is broadly contemplated by the present invention. While preferred embodiments and methods have been shown and described, it will be apparent to one of ordinary skill in the art that numerous alterations may be made without departing from the spirit or scope of the invention. For example, although in one embodiment ultracapacitors
25 are disclosed, it is understood that the present invention will find use with other types of devices, for example, conventional capacitors, including electrolytic, etc; and secondary batteries. Also, fuel cell and regenerative applications are only representative of some, but not all, applications envisioned for use of embodiments of the invention. Furthermore, resistors capacitors, inductors, and diodes
disclosed herein may be implemented using surface mount, thru hole, and other components known
30 by those skilled in the art; comparator, op amp, control circuits may be implemented by those skilled in the art using other circuits, amplifiers, transistors, resistors, and other components known to those skilled in the art; and transistors, may be implemented using amplifiers, FETs, NPN, PNP, and other components known to those skilled in the art. It is also envisioned that one or more components

disclosed herein may implemented in analog form or digital form, including as PLD, firmware, or software implementations. Specific circuit implementations are not provided to facilitate ease of reading and understanding, and as design and implementation of the embodiments described herein to achieve the present invention would be within the experience and ability of those skilled in the art.

- 5 [47] Therefore, the invention is not limited except in accordance with the following claims and their legal equivalents.

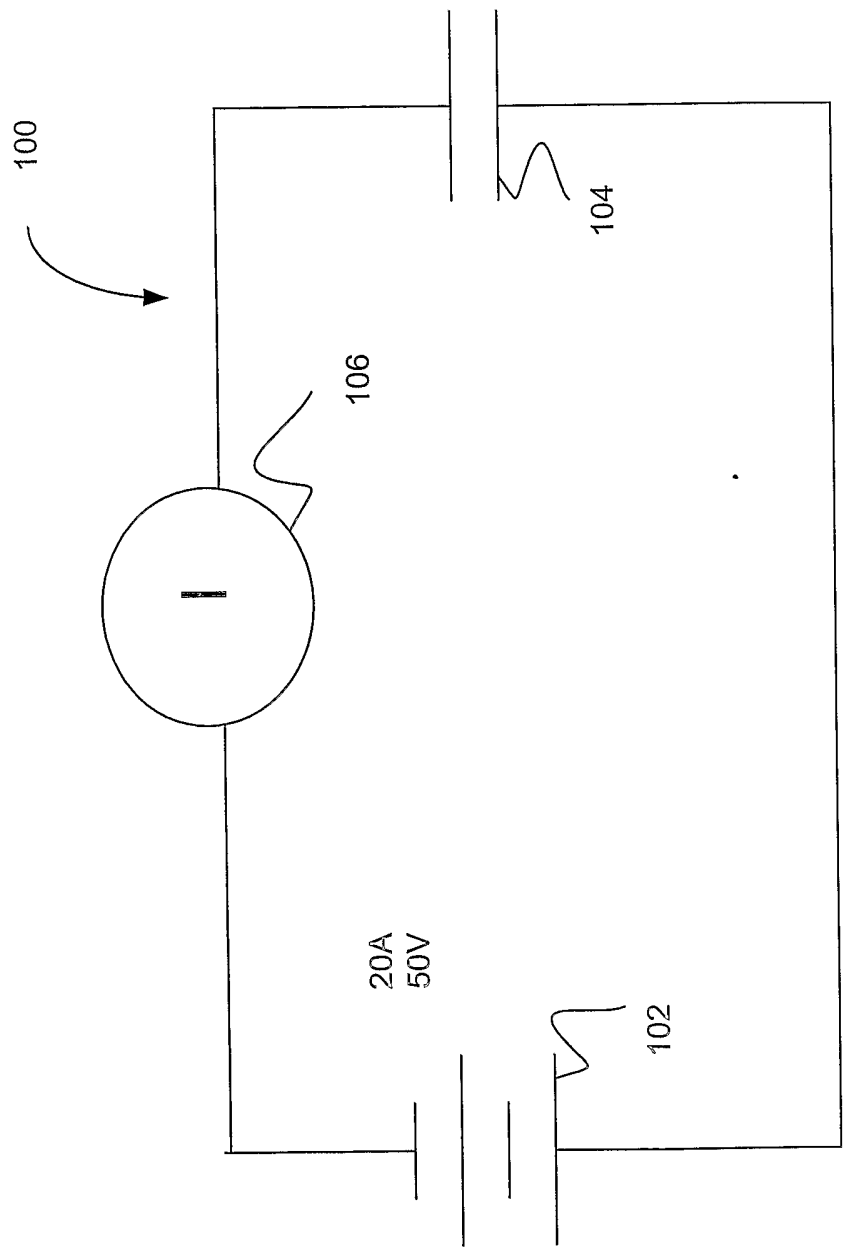
We Claim:

1. An arrangement for charging a power module, comprising:
 - a power module including one or more capacitors;
 - an energy source; and
 - 5 a control circuit coupled to the power module and to the energy source to provide a higher current level to said power module than output by said energy source for at least a portion of a charging period.
2. The arrangement according to Claim 1, wherein said control circuit is adapted to maintain a constant power level at the power module as the voltage level across the power module
10 increases.
3. The arrangement according to Claim 1, wherein said control circuit includes pulse-width modulator and an inductor connected in series with said power module.
4. The arrangement according to Claim 3, wherein said pulse-width modulator controls a charge level of said inductor.
- 15 5. The arrangement according to Claim 4, wherein said charge level corresponds to a current level which is in accordance with a desired power level at said power module and an instantaneous voltage level across said power module.
6. The arrangement according to Claim 3, wherein said inductor is adapted to limit a current level through said power module to a predetermined peak level.
- 20 7. The arrangement according to Claim 1, wherein said control circuit is adapted to provide a current level through said power module greater than a current level from said energy source during at least a portion of a charging period.
8. The arrangement according to claim 1, wherein the one or more capacitor comprises an ultracapacitors.
- 25 9. The arrangement according to claim 1, wherein the one or more capacitor comprises a value greater than about 1 Farad.
10. A constant-power charging circuit for an ultracapacitor power module, comprising:
 - a pulse-width modulator; and
 - an inductor connected in series with said pulse-width modulator and said power
30 module;
 - wherein said pulse-width modulator is adapted to control the charge level of said inductor.

11. The circuit according to Claim 10, wherein said charge level corresponds to a current level which is in accordance with a desired power level at said power module and an instantaneous voltage level across said power module.
12. The arrangement according to Claim 10, wherein said inductor is adapted to limit a current level through said power module to a predetermined peak level.
13. The arrangement according to Claim 10, wherein said control circuit is adapted to provide a current level through said power module greater than a current level from said energy source during at least a portion of a charging period.
14. A method of charging an capacitor power module, comprising:
 - 10 charging an inductor connected in series between an energy source and said power module; and
 - controlling a charge level of said inductor to achieve a desired current level through said power module.
15. The method according to Claim 14, wherein said controlling includes modulating the current from said energy source to said inductor through a pulse-width modulator.
16. The method according to Claim 14, wherein said desired current level corresponds to a desired power level at said power module.
17. The method according to Claim 16, wherein said power level is constant during charging of said power module.
18. The method according to Claim 14, wherein said desired current level through said power module is greater than a current level from said energy source during at least a portion of a charging period.
20. A constant power charge module, comprising:
 - 25 a power module including one or more capacitors;
 - an energy source;
 - a voltage sense circuit, the voltage sense circuit adapted to sense a voltage of the energy source and to output a signal when the voltage is sensed; and
 - a control circuit adapted to provide a higher current level to said power module than output by said energy source for at least a portion of a charging period of the constant power charge module and the signal.

21. The module of claim 20, wherein the one or more capacitors comprise a capacitance of about 1 Farad or more.
22. A constant power charge module, comprising:
one or more capacitor;
5 energy source means for providing a signal; and
control circuit means for provide a higher current level to the capacitor than output by said energy source for a least a portion of a charging period of the constant power charge module and the signal.
23. A method for charging a capacitor; comprising the steps of:
10 providing an energy source for charging the capacitor over a charging period; and
providing a higher current to the capacitor than output by the energy source for at least a portion of the charging period.
24. A regenerative apparatus, comprising:
one or more capacitors;
15 an energy source;
a voltage sense circuit, the voltage sense circuit adapted to sense a voltage of the energy source and to output a signal when the voltage is sensed; and
a control circuit adapted to provide a higher current level to said one or more capacitor than output by said energy source for at least a portion of a charging period of the
20 one or more capacitors and the signal.
25. The apparatus of claim 24, wherein the capacitors comprise ultracapacitors.
26. The apparatus of claim 25, wherein the energy source comprises a regenerative braking motor.

25



Prior Art

Figure 1A

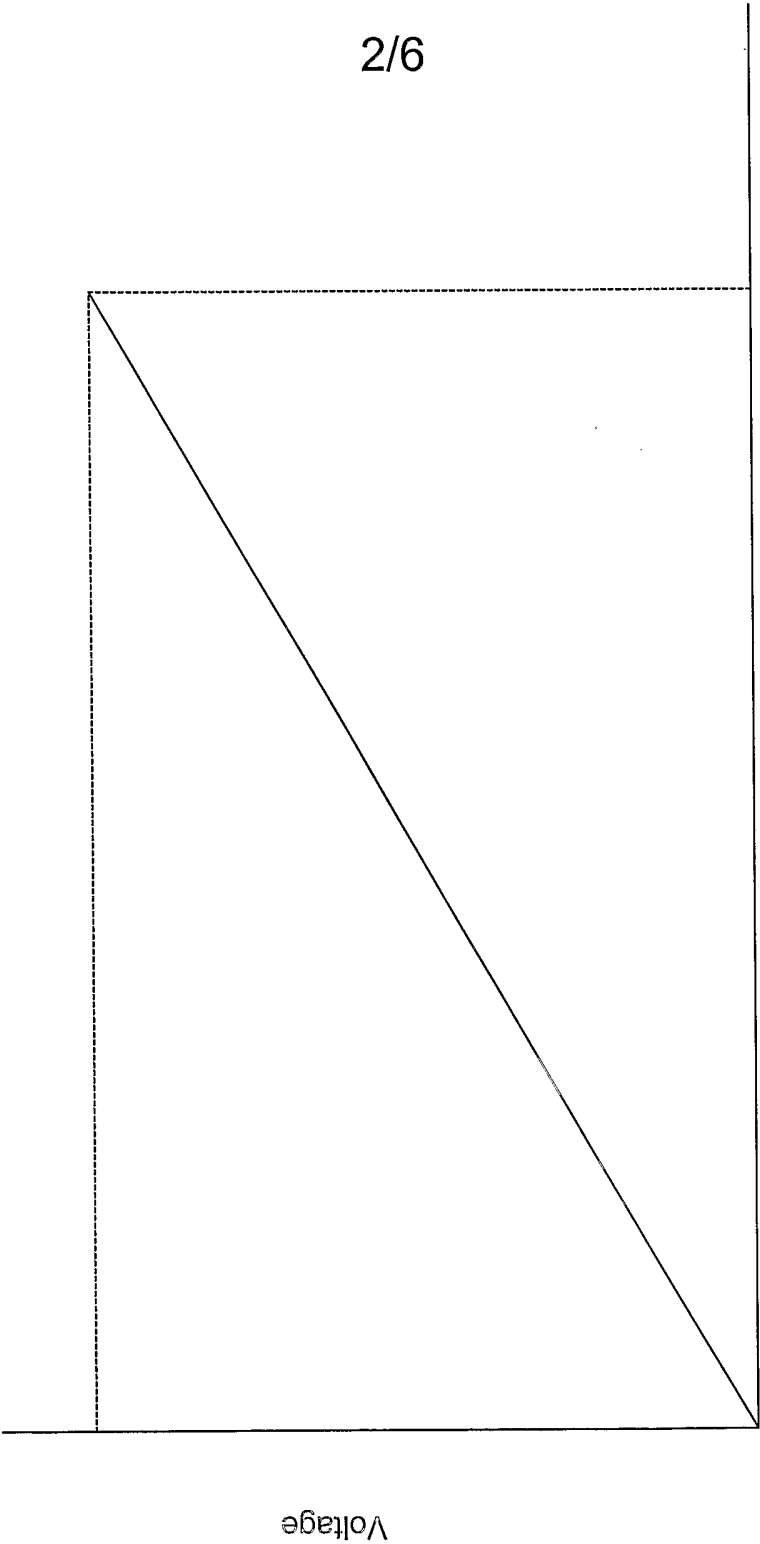


Figure 1b

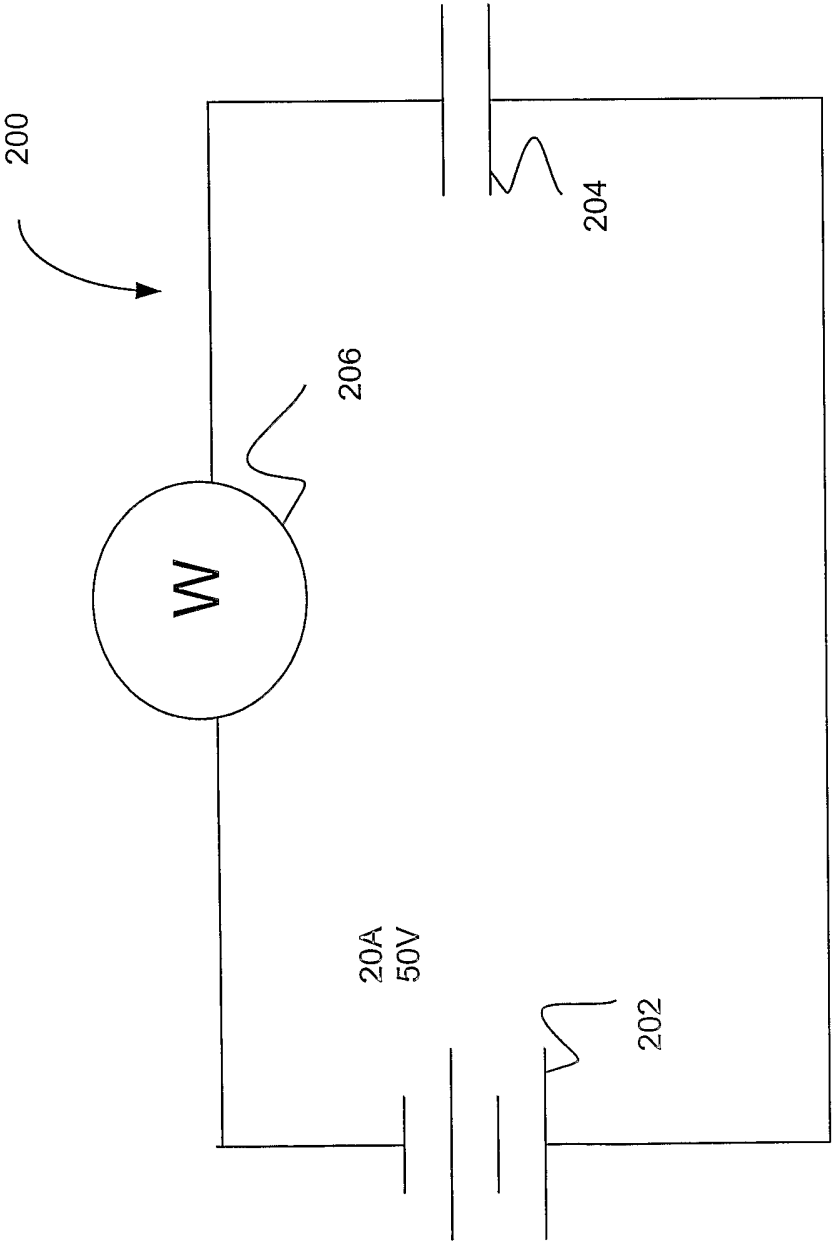


Figure 2A

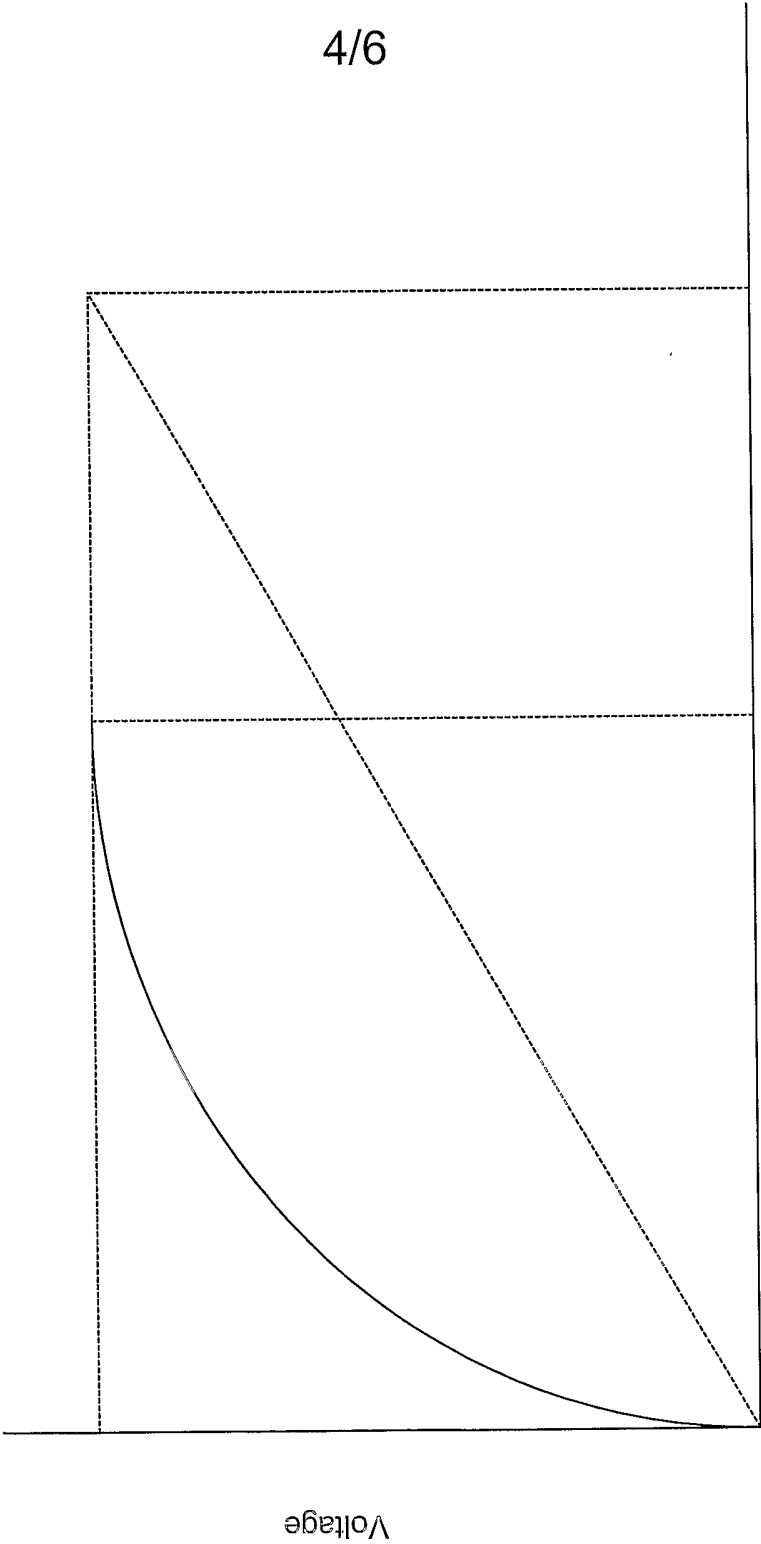
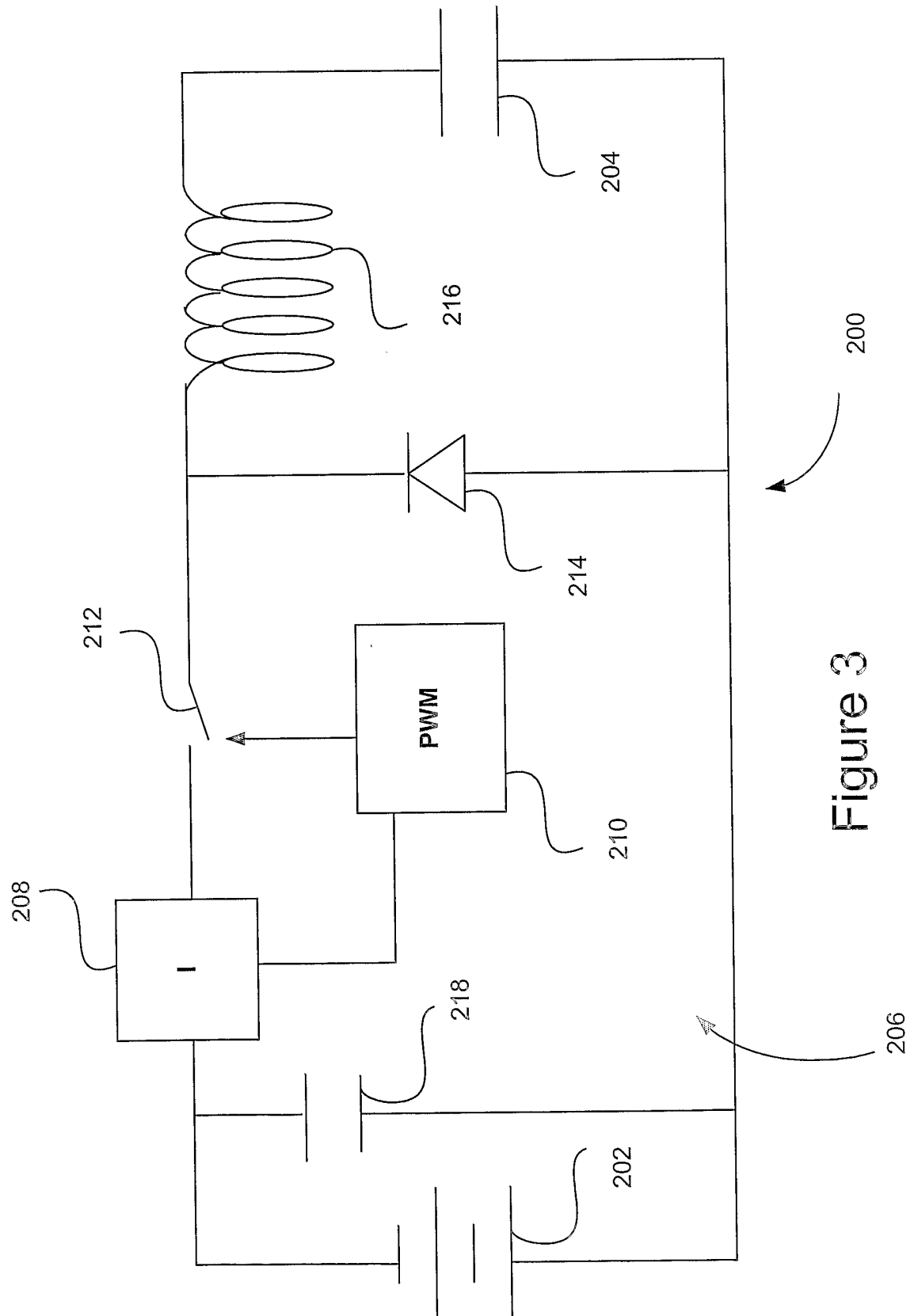


Figure 2b



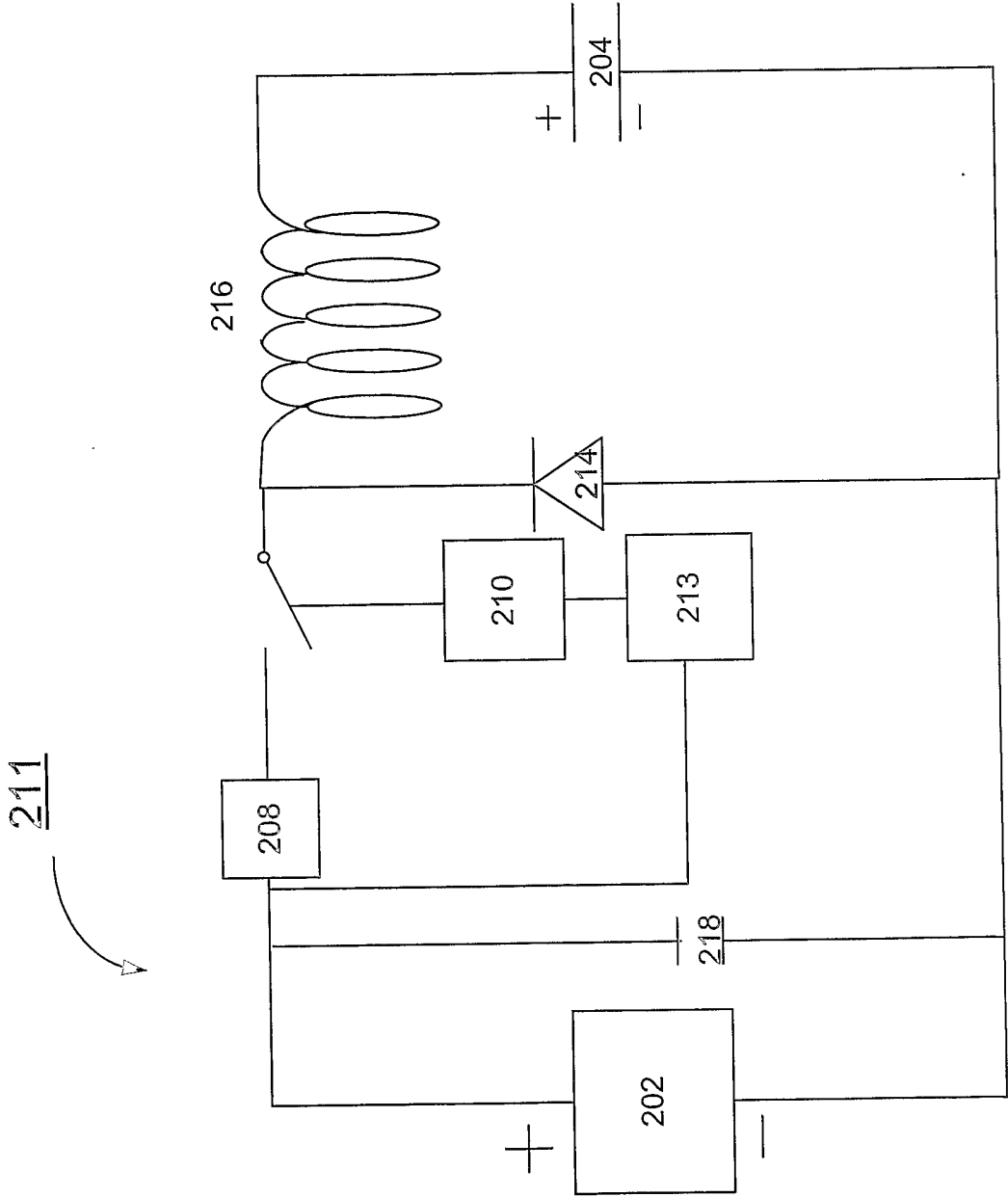


Figure 4