High voltage and low voltage switch mode circuits and methods serve to recover the charge stored on electro-luminescent lamp panels that would otherwise be dissipated during the discharge cycle of a drive circuit. The high voltage circuits and methods operate to transfer the charge to the high voltage rail, while the low voltage circuits and methods operate to transfer the charge to the source of low drive voltage.
Figure 1 (Prior Art)
Figure 6
Figure 8
Figure 9
Figure 14
SWITCH MODE ENERGY RECOVERY FOR
ELECTRO-LUMINESCENT LAMP PANELS

FIELD OF THE INVENTION
[0001] This invention relates generally to electro-luminescent lamp panels and, more particularly, to the recovery of energy stored in these panels that is otherwise dissipated during the discharge cycle of a drive circuit.

BACKGROUND AND SUMMARY OF THE INVENTION
[0002] Electro-luminescent lamps act as capacitors, electrically. These lamps store energy, as do all capacitors, in the form of an electrical voltage charge. In the normal electro-luminescent lamp driver circuit, this charge is dissipated, and therefore lost, during the discharge cycle of operation.
[0003] Electro-luminescent lamp driver circuits are well known in the prior art, exemplary of which are the Supertex HV803 and the Toko TK659XX. A typical one of these circuits is illustrated in FIG. 1. In that circuit, components L1, S0, D1, and C1 constitute a high voltage boost or step-up converter which receives a low voltage (less than 6 volts) and boosts it to between 20 and 100 volts on the capacitor C1. Components S1, S2, S3, and S4 constitute a H-bridge circuit that is used to commutate the high DC voltage on capacitor C1 into a high AC voltage across an electro-luminescent lamp capacitor (C lamp) that is about twice the DC voltage on capacitor C1. This AC voltage charges and discharges the capacitor C lamp, with the energy stored in the capacitor C lamp being dissipated in components S3 and S4 of the H-bridge during the discharge cycle.
[0004] It would be advantageous to recover this energy, existing in the form of charge at high voltage, from the electro-luminescent lamp capacitor C_lamp, and reuse it, thus making the entire electro-luminescent lamp driving system more efficient. Accordingly, the present invention is directed to circuitry required to implement the recovery of this otherwise lost energy, which is significant in the case of large electro-luminescent lamps that are driven to higher voltages.

BRIEF DESCRIPTION OF THE DRAWINGS
[0005] FIG. 1 is a circuit diagram of a typical prior art electro-luminescent lamp driver circuit that is unable to recover charge from the electro-luminescent lamp capacitor.
[0006] FIG. 2 is a schematic diagram of an electro-luminescent lamp driver circuit employing high voltage switch mode method of charge recovery, in accordance with one embodiment of the present invention.
[0007] FIG. 3 is a schematic diagram of an electro-luminescent lamp driver circuit employing an energy transfer capacitor, in accordance with another embodiment of the present invention.
[0008] FIG. 4 is a schematic diagram of an electro-luminescent lamp driver circuit employing an integrated high voltage switch mode method of charge recovery, in accordance with another embodiment of the present invention.
[0009] FIG. 5 is a waveform diagram illustrating typical waveforms generated by the electro-luminescent lamp driver circuits of FIGS. 2-4.

[0010] FIG. 6 is a schematic diagram of an electro-luminescent lamp driver circuit employing charge pump energy recovery, in accordance with another embodiment of the present invention.
[0011] FIG. 7 is a waveform diagram illustrating simulated waveform results obtained from the electro-luminescent lamp driver circuit of FIG. 6.
[0012] FIG. 8 is a schematic diagram of an electro-luminescent lamp driver circuit employing a low voltage switch mode method of energy recovery, in accordance with another embodiment of the present invention.
[0013] FIG. 9 is a schematic diagram illustrating the circuit equivalent of the circuit of FIG. 8 during a first cycle of operation.
[0014] FIG. 10 is a schematic diagram illustrating the circuit equivalent of the circuit of FIG. 8 during second and fourth cycles of operation.
[0015] FIG. 11 is a schematic diagram illustrating the circuit equivalent of the circuit of FIG. 8 during a third cycle of operation.
[0016] FIG. 12 is a waveform diagram illustrating the simulation of electro-luminescent lamp panel energy being returned to the low voltage source as a current, with the frequency of the transfer controller clock being constant with time.
[0017] FIG. 13 is a waveform diagram illustrating the simulation of electro-luminescent lamp panel energy being returned to the low voltage source as a current, with the frequency of the transfer controller clock increasing with time.
[0018] FIG. 14 is a schematic diagram of an electro-luminescent lamp driver circuit employing a low voltage switch mode method of energy recovery, integrated with a boost converter, in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION
[0019] Described below are a number of high and low voltage methods for the recovery of otherwise dissipated energy from electro-luminescent lamp panels. The high voltage methods generally return energy to the high voltage node of the electro-luminescent lamp driver circuit or to the electro-luminescent capacitor, while the low voltage methods return energy to a low voltage source.
[0020] Referring now to FIG. 2, there is shown an electro-luminescent lamp driver circuit employing a high voltage switch mode method of charge recovery in which a second boost converter is employed to discharge the voltage on the electro-luminescent lamp and return energy to a capacitor C1. This method increases the peak-to-peak voltage to the electro-luminescent lamp. An H-bridge operates normally to charge a capacitor C_lamp, as shown in the waveform diagram of FIG. 5. In discharging capacitor C_lamp, only switch S1 is opened, while switch S5 is closed, thereby applying the voltage on capacitor C_lamp to the input of the boost converter that employs components L2, S7, and D2. The switching frequency and duty cycle of switch S7 is selected to effect the most efficient transfer of energy from
capacitor \( C_{lamp} \) to capacitor \( C_1 \). After most of the charge on capacitor \( C_{lamp} \) is transferred, switch \( S5 \) opens and switch \( S3 \) closes, thereby discharging capacitor \( C_{lamp} \) completely. The charging cycle is repeated on the other side of the H-bridge by opening switch \( S4 \) and closing switch \( S6 \), while operating switch \( S7 \) as described above. After capacitor \( C_{lamp} \) is nearly discharged, switch \( S6 \) opens and switch \( S4 \) closes, following which switch \( S3 \) opens and switch \( S1 \) closes, thus beginning another AC voltage cycle of capacitor \( C_{lamp} \). The advantage of charge recovery is realized as an increased rate of rise in the voltage on capacitor \( C_1 \), as shown in the waveform diagram of Fig. 5, when switches \( S5 \) or \( S6 \) are closed and capacitor \( C_{lamp} \) is being discharged.

Referring now to Fig. 3, there is shown an electro-luminescent lamp driver circuit employing an alternative high voltage switch mode method of charge recovery in which an energy transfer capacitor \( C_{ET} \) is provided to the second boost converter to control the rate of discharge of the electro-luminescent lamp panel voltage. Switches \( S8 \)-\( S11 \) are controlled in a way similar to that described below in connection with Figs. 9-11.

Referring now to Fig. 4, there is shown an electro-luminescent lamp driver circuit integrated with the main boost converter as an alternative high voltage switch mode method of charge recovery. This circuit realizes a saving in the number of external components, but requires synchronization of timing between the charge recovery circuit and the main boost converter. Inductors \( L1 \) and \( L3 \) may utilize the same magnetic core. Operation of the circuit of Fig. 4 is similar to that of the electro-luminescent lamp driver circuit of Fig. 2, with regard to switches \( S0 \)-\( S6 \). However, there is a difference with regard to operation of switch \( S8 \), in that it must be synchronized with switch \( S0 \). Switch \( S8 \) must close after switch \( S0 \) closes, in order that the current beginning to flow through inductor \( L3 \) flows through switch \( S0 \) rather than back through inductor \( L1 \) to the low voltage supply \( Vdd \). In addition, switch \( S8 \) must remain closed for a short time after switch \( S0 \) opens to insure that the voltage at the anode of diode \( D1 \) has decayed to a level below low voltage supply \( Vdd \). Switch \( S8 \) should then open.

Referring now to Fig. 6, there is shown an electro-luminescent lamp driver circuit employing a holding capacitor \( C_{ER} \) to which energy is transferred in a particular cycle and from which energy is returned to capacitor \( C_{lamp} \) in a later cycle. Considering an initial state of this circuit in which switches \( S2 \) and \( S3 \) are closed, while all other switches are open, capacitor \( C_{lamp} \) is charged to a voltage at high voltage rail \( HV_{node} \) by a current flowing through diode \( D2 \) and switches \( S2 \) and \( S3 \). Next, switches \( S2 \) and \( S3 \) open, and switch \( S5 \) closes, thereby tying the right terminal of capacitor \( C_{lamp} \) essentially to the high voltage rail \( HV_{node} \) and moving the voltage at the left terminal of capacitor \( C_{lamp} \) above the voltage at high voltage rail \( HV_{node} \) by some amount. During this phase, diode \( D4 \) becomes forward biased, and a current flows from capacitor \( C_{lamp} \) into energy recovery capacitor \( C_{ER} \). The voltage on capacitor \( C_{ER} \) continues to rise until an equilibrium voltage is reached. Switch \( S4 \) now closes, while switch \( S5 \) remains closed. Capacitor \( C_{lamp} \) is then charged to the voltage at the high voltage rail \( HV_{node} \) by a current flowing through diode \( D3 \) and switches \( S4 \) and \( S5 \). Next, a portion of the energy in capacitor \( C_{ER} \) is returned to capacitor \( C_{lamp} \) by closing switch \( S7 \). Operation of the circuit of Fig. 6, as described above, is illustrated in the simulated waveform results diagram of Fig. 7.

Referring now to Fig. 8, there is shown an electro-luminescent lamp driver circuit employing a low voltage switch mode method of charge recovery in which a current is returned to the low voltage supply \( V \) by transferring energy from the electro-luminescent lamp panel through a switched capacitor/inductor arrangement. This circuit is referred to as a current limited circuit, since the return current is set by the topology and clock rate of the circuit. A group of four switching cycles are used repetitively to accomplish a transfer of energy between the electro-luminescent lamp panel and the low voltage supply \( V \).

Initially, a charge or voltage exists on the capacitor \( C_{lamp} \). This charge may have been deposited earlier by an H-bridge circuit similar to that described above, or by some other circuit configuration. An energy transfer capacitor \( C_{ET} \) is assumed to have no initial charge. An energy transfer inductor \( I_{ET} \) may or may not have an initial current.

Referring now to Fig. 9, during the first cycle of operation of the circuit of Fig. 8, switches \( S1 \) and \( S2 \) close to allow current to begin flowing from capacitor \( C_{lamp} \) through switch \( S1 \), capacitor \( C_{ET} \), switch \( S2 \), inductor \( I_{ET} \), and the low voltage supply \( V \). During this cycle, energy is being delivered to the low voltage supply \( V \) by means of a current flowing into its positive terminal.

After some period of time, a transfer controller opens switches \( S1 \) and \( S2 \), to begin a second cycle of operation of the circuit of Fig. 8, as illustrated in Fig. 10. At this point, a charge has been developed on capacitor \( C_{ET} \), and a current is flowing in inductor \( I_{ET} \). This current continues to flow in a recirculation diode \( DR \), while energy supplied by inductor \( I_{ET} \) is being delivered to the low voltage supply \( V \). The charge on capacitor \( C_{ET} \) and energy \((0.5 \times CV)^2 \) are relatively constant during this second cycle of operation.

During a third cycle of operation of the circuit of Fig. 8, illustrated in Fig. 11, the transfer controller closes switches \( S3 \) and \( S4 \) to cause a current flow from capacitor \( C_{ET} \) through switch \( S3 \), inductor \( I_{ET} \), switch \( S4 \), and back to capacitor \( C_{ET} \). The energy stored in capacitor \( C_{ET} \) is now being delivered through inductor \( I_{ET} \) to the low voltage supply \( V \).

During a fourth cycle of operation of the circuit of Fig. 8, illustrated in Fig. 10, the transfer controller opens switches \( S3 \) and \( S4 \). At this point, the voltage on capacitor \( C_{ET} \) is zero. The current flowing through inductor \( I_{ET} \) continues to flow in recirculation diode \( DR \), resulting in a transfer of energy from inductor \( I_{ET} \) to the low voltage supply \( V \).

The four cycles described above are repeated to incrementally transfer energy from capacitor \( C_{lamp} \) to the low voltage supply \( V \). Each incremental transfer is approximated by the expression \( E=0.5 \times C_{ET}(V \times CV)^2 \). In some implementations of the circuit of Fig. 8, only the first and third cycles are performed, back to back.

The voltage on capacitor \( C_{lamp} \) drops incrementally following each group of four cycles by the amount
Vint*(C_lamp/(C_lamp+C_ET)). By regulating how often each group of four cycles is repeated, the transfer controller can adjust the rate of decay of the voltage on capacitor C_lamp. Capacitor C_ET facilitates this control at practical switching frequencies. For example, without capacitor C_ET and using only inductor L_ET, the switch network may need to operate at approximately twenty times the normal frequency to achieve the same discharge profile of capacitor C_lamp.

[0032] Referring now to FIG. 12, there is shown a simulation during a 1 msec. time duration of the operation of the circuit of FIG. 8, given certain parameters. The initial charge on the 80 nF capacitor C_lamp is 100 volts. The transfer controller is a dual clock source, with the two outputs being 180 degrees out of phase. The clock frequency is constant at 1 MHz. The upper waveform shows the current flow back into the low voltage source V. The center waveform shows the exponential voltage decay on capacitor C_lamp as energy is being removed from it.

[0033] Alternatively, the frequency of the transfer controller can vary with time, thus producing a different waveform of the discharge of capacitor C_lamp, as illustrated in FIG. 13. The waveforms of FIG. 13 resulted from the same circuit as those of FIG. 12, except that the frequency of transfer controller increased linearly with time, thus producing a convex waveform of voltage decay on capacitor C_lamp as energy is being removed from it.

[0034] In an alternative embodiment of the circuit of FIG. 8, inductor L_ET can serve as a boost converter. Inductor L_ET_B, as illustrated in FIG. 14. In this arrangement, a first topology involving inductor L_ET_B, in combination with a switch Boost_FT, forms a step-up converter. Alternatively, a second topology involving inductor L_ET_B, in combination with capacitor C_ET, switches S1-S4, and a transfer controller, forms a low voltage energy recovery circuit. For example, consider a system which repetitively uses two operational phases to produce an AC waveform across capacitor C_lamp. In a first phase, the first topology described above is employed, whereby capacitor C_lamp is charged by the output of the step-up converter, possibly through a switching bridge, as illustrated in FIG. 1. In a second phase, the second topology described above is employed, and capacitor C_lamp is discharged by the energy recovery topology and method illustrated in FIG. 8. These two phases are repeated at a certain rate, causing the voltage across capacitor C_lamp to rise and fall at a desired frequency.

We claim:
1. A circuit for driving an electro-luminescent lamp panel, the circuit employing a high voltage switch mode for recovering charge stored on the electro-luminescent lamp panel, during a discharge cycle of operation of the circuit, the circuit comprising:
   a device coupled to a source of low voltage for driving the electro-luminescent lamp, the device comprising a first capacitor and a switching circuit for switchably connecting the electro-luminescent lamp panel across the first capacitor; and
   a step-up converter, coupled to the electro-luminescent lamp panel and the first capacitor for transferring charge from the electro-luminescent lamp panel to the first capacitor during the discharge cycle of operation.
2. A circuit as in claim 1, wherein the step-up converter operates synchronously with the device.
3. A circuit as in claim 1, further comprising a second capacitor in combination with a plurality of switches for controlling the rate of transfer of charge from the electro-luminescent lamp panel to the first capacitor during the discharge cycle of operation.
4. A circuit as in claim 2, further comprising a second capacitor in combination with a plurality of switches for controlling the rate of transfer of charge from the electro-luminescent lamp panel to the first capacitor during the discharge cycle of operation.
5. A circuit for driving an electro-luminescent lamp panel, the circuit employing a high voltage switch mode for recovering charge stored on the electro-luminescent lamp panel, the circuit comprising:
   a device coupled to a source of low voltage for driving the electro-luminescent lamp, the device comprising a first capacitor and a switching circuit coupled to the electro-luminescent lamp panel; and
   a second capacitor, switchably coupled to the electro-luminescent lamp panel, to which charge is transferred from the electro-luminescent lamp panel during a particular cycle of operation of the circuit, and from which charge is transferred to the electro-luminescent lamp panel during a later cycle of operation of the circuit.
6. A circuit for driving an electro-luminescent lamp panel, the circuit employing a low voltage switch mode for recovering charge stored on the electro-luminescent lamp panel, during one or more cycles of operation of the circuit, the circuit comprising:
   a source of low voltage;
   an energy transfer inductor, coupled to the source of low voltage; and
   a transfer controller, switchably coupled to the energy storage inductor and the electro-luminescent lamp panel, for controllably transferring charge from the electro-luminescent lamp panel to the source of low voltage.
7. A circuit as in claim 6, further comprising an energy transfer capacitor, switchably coupled to the energy storage capacitor and the electro-luminescent lamp panel.
8. A circuit for driving an electro-luminescent lamp panel, the circuit employing a low voltage switch mode for recovering charge stored on the electro-luminescent lamp panel, during one or more cycles of operation of the circuit, the circuit comprising:
   a source of low voltage;
   an energy transfer capacitor, switchably coupled to the source of low voltage and to the electro-luminescent lamp panel; and
   a transfer controller, switchably coupled to the energy storage capacitor and the electro-luminescent lamp panel, for controlling the transfer of charge from the electro-luminescent lamp panel to the source of low voltage.
9. A circuit as in claim 6, wherein the transfer controller operates at a constant frequency.

10. A circuit as in claim 9, wherein the transfer controller comprises a dual clock source having two outputs 180 degrees out of phase with each other.

11. A circuit as in claim 7, wherein the transfer controller operates at a constant frequency.

12. A circuit as in claim 11, wherein the transfer controller comprises a dual clock source having two outputs 180 degrees out of phase with each other.

13. A circuit as in claim 8, wherein the transfer controller operates at a constant frequency.

14. A circuit as in claim 13, wherein the transfer controller comprises a dual clock source having two outputs 180 degrees out of phase with each other.

15. A circuit as in claim 6, wherein the transfer controller operates at a frequency that varies with time.

16. A circuit as in claim 7, wherein the transfer controller operates at a frequency that varies with time.

17. A circuit as in claim 8, wherein the transfer controller operates at a frequency that varies with time.

18. A circuit as in claim 15, wherein said frequency increases linearly with time.

19. A circuit as in claim 16, wherein said frequency increases linearly with time.

20. A circuit as in claim 17, wherein said frequency increases linearly with time.

21. A circuit for driving an electro-luminescent lamp panel, the circuit employing a low voltage switch mode for recovering charge stored on the electro-luminescent lamp panel, during one or more cycles of operation of the circuit, the circuit comprising:

a source of low voltage;

a step-up converter coupled to a source of low voltage for driving the electro-luminescent lamp, the step-up converter comprising an inductor, a switch, a diode, and a first capacitor;

a second capacitor, switchably coupled to the inductor; and

a transfer controller, switchably coupled to the inductor, the second capacitor, and the electro-luminescent lamp panel, for controlling the transfer of charge from the electro-luminescent lamp panel to the source of low voltage.

22. A method for recovering energy stored on an electro-luminescent lamp panel, the method comprising:

applying a first voltage present across the electro-luminescent lamp panel to an input of a switch-mode energy conversion circuit;

operating the switch-mode energy conversion circuit to transform energy representative of said first voltage to a second voltage that is higher than said first voltage;

applying said second voltage to a storage device; and
delivering energy stored in said storage device back to said electro-luminescent lamp panel.

23. A method for recovering energy stored on an electro-luminescent lamp panel, the method comprising:

applying a first voltage present across the electro-luminescent lamp panel to an input of a switch-mode energy conversion circuit;

operating the switch-mode energy conversion circuit to transform energy representative of said first voltage to a second voltage that is higher than said first voltage;

applying said second voltage to a storage device; and
delivering energy stored in said storage device to an electro-luminescent lamp panel driver circuit.

24. A method for recovering energy stored on an electro-luminescent lamp panel, the method comprising:

applying a first voltage present across the electro-luminescent lamp panel to an input of a switch-mode energy conversion circuit;

operating the switch-mode energy conversion circuit to transform energy representative of said first voltage to a second voltage that is higher than said first voltage;

applying said second voltage to a storage device; and
delivering energy stored in said storage device back to said electro-luminescent lamp panel and to an electro-luminescent lamp panel driver circuit.

25. A method for recovering energy stored on an electro-luminescent lamp panel, the method comprising:

applying a first voltage present across the electro-luminescent lamp panel to an input of a switch-mode energy conversion circuit;

operating the switch-mode energy conversion circuit to transform energy representative of said first voltage to a current;

delivering said current to a source of operating voltage for said electro-luminescent lamp panel to thereby realize a reduction in average output current required from said source of operating voltage to operate said electro-luminescent lamp panel.

26. A method as in claim 25, further comprising the step of controlling an amplitude versus time characteristic of said current delivered to said source of operating voltage.

27. A circuit as in claim 1, wherein said device comprises a primary step-up converter, including an inductor, a switch, and a diode.

28. A circuit as in claim 5, wherein said device comprises a primary step-up converter, including an inductor, a switch, and a diode.