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DESCRIPTION

FIELD OF THE INVENTION

[0001] This invention relates generally to power conversion. More particularly, this invention relates to an efficient DC-to-DC converter operable through wide voltage swings.

BACKGROUND OF THE INVENTION

[0002] There is a growing demand for DC-to-DC converters with improved conversion efficiency and reduced size. Design techniques vary, with some techniques reducing the voltage or current, others increasing the voltage or current, and still others alternately increasing or decreasing voltage or current. In a typical DC-to-DC converter, one or more switches connect to input power, a capacitor or inductor stores excess energy in one phase, and in another phase the stored energy is released to output nodes.

[0003] Each technique has its own advantages and disadvantages. There are multiple tradeoffs between component sizes, overall efficiency and optimal zones of input to output voltage ratios. For example, increasing switching frequency usually results in a reduction of component size, but concomitantly increase switching losses due to parasitic capacitances and switch transition losses. As a result overall efficiency is reduced.

[0004] A common method of AC-to-DC conversion is to use a Bridge Rectifier to convert AC input to DC, and then use a DC-to-DC switching converter to generate the proper DC output. Past attempts to simultaneously meet the objectives of improving conversion efficiency and reducing the converter size have been dominated by overall efficiency concerns. Efficiency is particularly important over a wider input to output voltage ratio, as experienced in AC-to-DC conversions. An AC source usually goes through a wide range of momentary voltages in each cycle, hindering any attempt to optimize a DC-to-DC converter for a specific input to output voltage ratio.

[0005] One approach to overcome the adverse effect of big variations in input voltage is to store charge in a storage capacitor, and to use the stored charge at the times the AC input voltage is below a certain level, referred to as a "transition period". There are two disadvantages associated with this method. First, a relatively large capacitor is required to store enough energy through a transition period. Second, during transition periods small or no current is drained from the input, which results in electrical current drain from the input AC line to transpire over a narrower time frame, mostly around peak input voltages. This eventually results in inefficient power transfer and a lower Power Factor.

[0006] Switching converters can be classified into three major converter classes based upon

the number of active power switches employed. The two-switch converter class includes buck, boost and flyback converters. The three-switch converter class includes forward converters. The four-switch converter class includes half-bridge and push-pull switching DC-to-DC converters. The switches may be active or passive. An active switch is controlled by modulating a gate. A passive switch, such as a diode, does not require a separate control. US 2004/0070376 A1 discloses all the features according to the preamble of claim 1 (the topology, see Fig. 1).

[0007] US 2008/100273 A1, discloses a power converter comprising coupled inductors and which can act according to a buck or to a boost operation depending on the input voltage (see Fig. 5).

[0008] In view of the foregoing, it would be desirable to provide improved techniques for power conversion. In particular, it would be desirable to provide reduced switching losses and reduced component sizes in a converter utilized in connection with wide voltage swings.

SUMMARY OF THE INVENTION

[0009] An embodiment of the invention includes a DC-to-DC converter comprising: a DC-input comprising a positive input terminal and a negative input terminal, a DC-output comprising a positive output terminal and a negative output terminal, two or more inductors coupled to a common core; three switches including two or more active switches, a controller configured to control operation of the DC-to-DC converter by controlling the active switches; a positive input branch, a negative input branch, a positive output branch, a negative output branch and an internal branch, and a positive internal node and a negative internal node; wherein: the positive input branch is connected between the positive input terminal and the positive internal node; the negative input branch is connected between the negative input terminal and the negative internal node; the internal branch is connected between the positive internal node and the negative internal node; the positive output branch is connected between the positive internal node and the positive output terminal; the negative output branch is connected between the negative internal node and the negative output terminal; wherein: the first of the at least two coupled inductors is located in series with the DC-input, either in the positive input branch or in the negative input branch; the second of the at least two coupled inductors is located in series with the DC-output, either in the positive or in the negative output branch; the first of the at least two active switches is located in series with the DC-input, either in the positive input branch or in the negative input branch the internal branch consists of the second of the at least two active switches; and the remaining third switch is located in series with the DC-output, either in the positive output branch or in the negative output branch; wherein the controller is further configured to select a DC-DC topology among a set of more than one possible DC-DC topologies based on the input voltage of the DC-input, by controlling the at least two active switches so that one of the three switches is forced to conduct current permanently according to the selected topology, as long as the selected topology does not change, the remaining two switches are forced to alternately conduct current in a complementary way such that the total

number of inductors conducting current is alternately changed and the DC-DC power conversion is performed according to the selected topology.

[0010] Another embodiment of the invention includes a DC-to-DC converter comprising: a DC-input comprising a positive input terminal and a negative input terminal, a DC-output comprising a positive output terminal and a negative output terminal, two or more inductors coupled to a common core; four switches including two or more active switches, and a controller configured to control operation of the DC-to-DC converter by controlling the active switches in order to select a DC-DC topology among a set of more than one possible DC-DC topologies based on the input voltage of the DC-input; a positive input branch, a negative input branch, a positive output branch, a negative output branch, a positive internal branch, a negative internal branch, a first parallel internal branch and a second parallel internal branch and a first positive internal node, a second positive internal node, a first negative internal node and a second negative internal node; wherein: the positive input branch is connected between the positive input terminal and the first positive internal node; the negative input branch is connected between the negative input terminal and the first negative internal node; the first parallel internal branch is connected between the first positive internal node and the first negative internal node; the positive internal branch is connected between the first positive internal node and the second positive internal node; the negative internal branch is connected between the first negative internal node and the second negative internal node; the second parallel internal branch is connected between the second positive internal node and the second negative internal node; the positive output branch is connected between the second positive internal node and the positive output terminal; and the negative output branch is connected between the second negative internal node and the negative output terminal; wherein: the first of the at least two coupled inductors is located in series with the DC-input, either in the positive input branch or in the negative input branch; the second of the at least two coupled inductors is located in series with the DC-output, either in the positive or in the negative output branch; the first of the at least two active switches is located in series with the DC-input, in the positive input branch; the first parallel internal branch consists of the second of the at least two active switches; the third switch is located either in the positive internal branch or in the negative internal branch; and the second parallel internal branch consists of the fourth switch; wherein, by controlling the two to four active switches, the controller is configured to permanently force one of the switches to conduct current permanently according to the selected topology, as long as the selected topology does not change such that:

- the operation of the DC-to-DC converter is according to a boost operation when the first active switch is forced permanently on and the remaining active switches are controlled such that the second active switch and the third switch alternately conduct current in a complementary way;
- the operation of the DC-to-DC converter is according to a flyback operation when the second active switch is forced permanently on and the remaining active switches are controlled such that the first active switch and the fourth switch alternately conduct current in a complementary way;
- the operation of the DC-to-DC converter is according to a buck operation when the third

switch is an active switch and is forced permanently on and the remaining active switches are controlled such that the first active switch and the fourth switch alternately conduct current in a complementary way or when the third switch is a diode and the remaining active switches are controlled such that the first active switch and the fourth switch alternately conduct current in a complementary way.

[0011] A comparative example includes a method of converting DC power. A DC input is received. Control signals are applied to active switches, where the control signals have alternating duty cycles between 25% and 100%. The DC input is driven, in response to the control signals, through at least one of two or more

[0012] The disclosed techniques reduce switching duty cycle variation to yield improved efficiency. Duty cycle variations are used to implement a range of voltage or current ratios. As duty cycles change to accommodate different transfer ratios, switch loss can increase due to the effect of parasitic capacitances and/or switch transition loss. The invention utilizes one or more switches as a switching mode changer. This reduces the need for dramatic changes in switching duty cycles, while still achieving a large voltage or current transfer ratio.

BRIEF DESCRIPTION OF THE FIGURES

[0013] The invention is more fully appreciated in connection with the following detailed description taken in conjunction with the accompanying drawings, in which:

FIGURES 1a-1j illustrate various embodiments of a three-switch implementation of the invention.

FIGURES 2a-2d illustrate various embodiments of the three-switch implementation employing passive switches.

FIGURES 3a-3d illustrate various embodiments of a four-switch implementation of the invention.

FIGURES 4a-4e illustrates various embodiments of a four-switch implementation employing passive switches.

FIGURES 5a-5b illustrate embodiments of the invention with an isolated output.

FIGURES 6a-6b illustrate the disclosed circuits of the invention in a daisy chain configuration.

FIGURES 7a-7b illustrate flicker reduction circuits configured in accordance with embodiments of the invention.

FIGURE 8a illustrates an AC-to-DC converter incorporating a three switch embodiment of the invention.

FIGURE 8b illustrates an AC-to-DC converter incorporating a four switch embodiment of the invention.

[0014] Like reference numerals refer to corresponding parts throughout the several views of the drawings.

DETAILED DESCRIPTION OF THE INVENTION

[0015] Figures 1a-1j illustrate various embodiments of a three-switch implementation of the invention. Observe that switch A is always in the input pathway and switch C is always in the output pathway. Depending upon the status of switch B and/or switch C, inductor energy storage can be through L1 only, or L1 and L2 in series.

[0016] In Figure 1a, switch A can be a master toggling switch to achieve a step down (buck) conversion. The state of switch B is the inverse of the state of switch A. Switch C is always on. For example, when switch A is closed switch B is open so whenever input voltage is higher than output voltage a positive current passes through L1, switch A, Switch C and L2 to the output. Opening switch A and closing switch B disconnects the input. Consequently, stored energy in inductor L2 releases to output through switch C and switch B.

[0017] This configuration is in contrast to a buck converter where inductor energy storage and release pathways use both L1 and L2. In Figure 1a in a typical case where $L1 = L2 = Lx$, the effective inductance of a buck converter is around $4 \cdot Lx$ during energy storage inside the inductor core. In Figure 1a, only L2 is in the energy release pathway so the effective inductance equals Lx .

[0018] In another operational embodiment of Figure 1a, switch B is turned on and switch C is configured as the inverse state of switch A. Thus, when switch A is on energy is stored in inductor L1, regardless of output voltage. When switch A turns off, L2 inductor energy releases through switch C and switch B. This configuration behaves as a flyback converter where input and output share a line. For example, when $L1 = L2 = Lx$, the energy storage and release pathways see Lx , representing a 1-to-1 ratio flyback conversion. Selecting different values for L1 and L2 and altering duty cycles can generate different effective current or voltage transfer ratios in this mode.

[0019] In a third configuration, the circuit of Figure 1a emulates a boost (step up) mode of operation. Here, switch A is always on, and switch C is configured as the inverse state of switch B. Turning switch B on stores energy in inductor L1. Turning switch B off releases inductor energy through L1, L2, switch A and switch C. Where $L1 = L2 = Lx$, the inductor energy release pathway equals $4 \cdot Lx$.

[0020] Switch A, B or C can operate in phase, out of phase, with overlapping duty cycles, or without overlapping duty cycles, or even randomly. Preselected L1 and L2 values can generate very wide effective current or voltage transfer ratios. This is achieved with only one physical inductor (L1 and L2 are on the same core), and at least three switches. Capacitors can be optionally added to different nodes in the system to reduce input and output ripple currents and/or voltages.

[0021] Switching losses are maintained at a minimum by minimizing duty cycle changes across a very wide input voltage range. For example, when the input voltage is significantly lower than the output voltage, boost mode can be selected. When the input to output ratio is closer to the ratio of L1 to L2, a flyback equivalent behavior is selected. When the input goes over a certain threshold higher than the output voltage a buck mode is selected.

[0022] Consider again the example where $L1 = L2 = Lx$. Also assume that an ideal output voltage (V_o) is $1/3$ of the peak input voltage (V_i), $V_o = V_i \text{ peak} / 3$. When configured for buck mode operation, during peak input voltage switch A sees a $4*Lx$ inductance. As both windings are on the same core, inductance saturation current (I_{sat}) is half of when only one winding receives current. The inductance effective voltage is $V_i - V_o = 3*V_o - V_o = 2*V_o$. The time required to saturate the inductor core is proportional to inductance and inductor saturation current, and is inversely proportional to the voltage: $(4*Lx*I_{sat}/2) / (2*V_o) = Lx*I_{sat}/V_o$.

[0023] Now assume that the input voltage is closer to V_o ($1/3$ of V_i peak in this example), and the flyback mode is selected. In this mode input inductance is Lx and voltage across L1 is $V_i = V_o$. The time required to saturate the inductor core is proportional to: $Lx*I_{sat}/V_o$. So even though the input voltage is $1/3$ of the peak voltage, the time required to saturate the inductor core is the same.

[0024] For the boost mode, switch A is always ON, input current drain occurs both when switch B is on and off. This can increase input current drain. So at half the input voltage, compared to the flyback mode, the same power is drained from the input. This further expands the input voltage range that can drain input power, while maintaining a narrower switching frequency and with less variation of duty cycles compared to conventional methods.

[0025] To see the effect of this method on switching loss, assume that all coils and all switches have no parasitic resistance and that there is no other source of loss except the switches parasitic capacitances and transition losses. In the above mentioned example where $L1 = L2 = Lx$, at peak input voltage where a buck mode is used, only a 50% duty cycle on switch A is enough to reach a V_o equivalent to $1/3$ of peak input voltage. A typical MOSFET capable of switching at a few hundred volts and current capability of a few amperes usually has switch transition times of around ten nanoseconds, and parasitic capacitances of around hundreds of picofarads. A quick calculation of switch switching loss would be: $P_{sw} = (V*I*(t_{RISE} + t_{FALL}))/2T$ where P_{sw} is switch power loss, V is the voltage across the switch while the switch is off, I is the switch current, t_{RISE} and t_{FALL} are the switch rise and fall times, and T is the switching period. If t_{RISE} and t_{FALL} are 10nS, one may want to limit switching frequency to

around 1MHz to keep switch transition loss to less than 2% on each active switch (switch A and B). Let's assume the input voltage is 300V and the input current is 1A. With a 50% duty cycle, input power is $300 \times 1 \times 50\% = 150\text{W}$. With 4% total loss (roughly 2% on switch A and 2% on switch B), efficiency would be 96% and 144W is transferred to output. For an output ideal voltage of $1/3$ of 300V ($300/3 = 100\text{V}$), this generates an output of 1.44A. In this scenario, 6W is lost in switches A and B combined. Now assume an input voltage that is $1/9$ of the input peak voltage ($300/9 = 33.33$ volts) and boost mode is selected. A 50% duty cycle switching on switch B and C generates 100V at the output. The inductor discharge pathway is L1 and L2 so the total power drained from the input is $(33.33 \times 2 \times 50\% + 33.33 \times 1 \times 50\%) = 50\text{W}$. This can be achieved at 333.33KHz, so the total switching loss is insignificant at around 1.33%. In this case, 49.33W is transferred to the output and 0.67W is lost in switches B and C.

[0026] In the above example of the invention, the minimum efficiency was 96% at peak input voltage using a coil with saturation current of 1A on both windings L1 and L2 in series. This stands in contrast to a prior art flyback converter. To achieve the same level of low voltage performance from a prior art flyback converter, a 1 to 3 ratio transformer is required. With this ratio, a 33.33V input voltage and 50% duty cycle on input and output switches generates a 100V at the output and comparable efficiency. Now if the input voltage increases to 300V, the duty cycle needs to be reduced to 10% to generate 100V at the output with the same 1 to 3 transformer ($300 \times 3/1 \times (10\%/90\%) = 100\text{V}$). This means that relative switching loss increases by a factor of 5 (50% in this invention versus 10% using a flyback converter) and input power drain is divided by 5 ($300\text{V} \times 1\text{A} \times 10\% = 30\text{W}$).

[0027] In summary, this means that in a prior art flyback converter at 300V input voltage, compared to this invention, the total input power drain and subsequently output power delivery is reduced by a factor of five (30W instead of 150W). To compensate for this loss in a prior art flyback converter, the only option is to increase inductor saturation current and inductor storage capacity 5 fold, increasing ON state input current to 5A, and reducing switching frequency by a ratio of 5 to compensate for increase in P_{sw} . Inductance increase and saturation current increase by 5 times roughly means more than a 5 times increase in coil size. As input current has increased and frequency of operation has reduced, to maintain the same input ripple voltage, input capacitors need to be $5 \times 5 = 25$ times larger. An increase in inductance is accompanied by an increase in inductor parasitic resistance.

[0028] Thus, in the prior art, component size needs to be increased to compensate for lost duty cycle. The invention does not have this problem because there are only small variations in duty cycles. In practice the invention's space saving can amount to more than one order of magnitude when compared to the prior art. Most state of the art high voltage switching regulators are limited by around one hundred kilohertz switching operations due to switching loss concerns. The invention is able to operate in excess of 500KHz switching frequency in the case of 150W from 300V input to 100V output, and in excess of 95% efficiency. At the same time, total component volume is reduced 10 to 30 times. A significantly smaller input capacitor (25 times smaller in the above example) enables a designer to use high reliability capacitors, such as ceramic capacitors instead of ordinary electrolytic capacitors. This is very important in

designing high reliability power supplies. An electrolytic capacitor's life is usually around a couple of thousand hours at 105°C or so, while ceramic capacitors can last several decades in similar conditions.

[0029] Observe that in each configuration switch A is in the input pathway and can be used to monitor input load properties. Switch C is always in output pathway and can be used to monitor output load properties. This is especially beneficial when a designer intends to monitor the Power Factor of the system and adjust switching frequency or switch duty cycle to maintain certain input or output load properties. For example, input current can be adjusted to mimic a near resistive behavior based on input voltage to achieve a Power Factor very close to 1. Alternately, input current or total input power can be adjusted for a fairly constant value. An increase in input current at lower input voltages compared to effective equivalent input resistance generates a "dynamic negative resistance", which means input equivalent impedance is reduced at lower input voltages. In a home or industrial environment this can be used to compensate for non-linear current drain of other major devices loaded on AC line and increase grid power line efficiency in some cases.

[0030] Figure 1b is similar to Figure 1a, but switch A and inductor L1 have changed positions, with switch A connected directly to the input followed by inductor L1. Figure 1c is similar to Figure 1a, but switch C and inductor L2 have changed positions, with switch C connected directly to the output following inductor L2. Figure 1d is similar to Figure 1a, but switch A is at the input and switch C is at the output, with inductors L1 and L2 sharing a common wire.

[0031] Figure 1e illustrates a configuration where switch C and L2 are in a return pathway of the output. Figure 1f is similar to Figure 1e, but switch A and inductor L1 have changed positions, with switch A being directly connected to the input, followed by inductor L1. Figure 1g is similar to Figure 1e, but switch C and inductor L2 have changed positions, with switch C directly connected to the output. Figure 1h is similar to Figures 1g, but switch A is directly connected to the input.

[0032] Figure 1i is similar to Figure 1e, but switches A and C are in the return pathway and inductors L1 and L2 share a common wire. Figure 1j is similar to figure 1e, but switch A is in the input return pathway and inductor L2 is in the output return pathway.

[0033] Figures 2a-2d illustrate a three switch implementation with at least one passive switch (*i.e.*, a switch that is not actively controlled; a diode is a passive switch). Figure 2a is the same as Figure 1a, but switch C is a diode. Figure 2b is the same as Figure 1e, but switch A is a diode. In Figure 2c, switch C is a diode and inductor L2 is in the output return pathway. In Figure 2d, switch A is a diode and switch C is in the output return pathway.

[0034] Another embodiment of the invention utilizes four switches. One benefit of this configuration is simpler switch control. Figures 3a-3d illustrate various four switch embodiments of the invention. Figure 3a is an expanded version of the three-switch configuration in Figure 1a, where a switch D is added. Figure 3b is similar to Figure 3a, but

switch C is in the junction between input and output return pathways. Figure 3c is similar to Figure 3a, but inductor L2 is in the output return pathway. Figure 3d is similar to Figure 3b, but inductor L2 is in the output return pathway.

[0035] Figures 4a-4e show versions where one or two of the actively controlled switches are replaced with diodes. Figure 4a is the same as Figure 3a, but switch D is a diode. Figure 4b is the same as Figure 3a, but switch C is a diode. Figure 4c is the same as Figure 3a, but both switches C and D are diodes. Figure 4d is the same as Figure 3a, but both switches A and D are diodes. Figure 4e is the same as Figure 3a, but switch A is a diode.

[0036] Figure 4c is a simplified version of Figure 4a where two of the actively controlled switches have been replaced with diodes. In Figure 4c, when switch B is closed, switch A can toggle to effectively act as a flyback converter with a shared line. L1 acts as a primary and L2 acts as a secondary of a transformer.

[0037] For the circuits of Figures 4a-4e, when switch B is open, toggling switch A results in a buck converter. In this condition, the output voltage is always lower than the input voltage. When switches A and C are closed and V_i is higher than V_o , positive current passes through L1, switch A, C and L2. As a result, energy is stored in L1 and L2. When switch A opens, L2 and switch D act as conduction path and energy is transferred to the output.

[0038] In a different configuration, switch B is closed and toggling switch A results in a flyback converter with a common line between input and output. In this condition, the output voltage can be lower or higher than the input voltage. When switch A is closed and switch C is open, regardless of output voltage, current passes through L1, switch A and switch B. As a result, energy is stored in L1. When switch A opens, L2 and switch D act as a conduction path and energy is transferred to the output.

[0039] In another configuration, switch A is on and switch B is used to toggle on and off. In this case, the converter acts as a modified boost converter. When switch B is on and switch C is off, regardless of output voltage, current flows through switch A, B and L1. Thus, L1 stores energy. When switch B turns off and switch C turns on, inductor energy from L1 and L2 is applied to the output.

[0040] Other combinations of toggling switch A and B with overlapping duty cycles can be used to achieve other voltage or current transfer ratios. This enables different current or voltage transfer ratios and other switching behaviors, including an equivalent Split-pi topology.

[0041] One advantage of the invention is the simplified control scheme to implement buck-boost functions. In all scenarios, switch A is always in the input current pathway toggling the input current. In one scenario switch B can act as transfer ratio "mode changer" to select between flyback and buck converter modes. These two switches can operate in conjunction, or independent from each other. Independent operation of these two switches can make the design of high voltage DC-to-DC and AC-to-DC converters much easier. For example, switch A

can be activated depending on its current, and switch B can be activated based on momentary input voltage level. This lets switch A work at high frequency and very high voltages, without need for any communication to other switches. Designing a high speed communication pathway capable of working at high voltage differences is a challenge, and one major limiting factor for switched high voltage DC-to-DC converters. As switch A is always in the input current pathway, the same switch can be used to monitor input load properties and to make adjustments necessary for a desired Power Factor.

[0042] One advantage of the invention is wider arbitrary transfer ratios. Since both L1 and L2 are on the same core, when input power passes through both L1 and L2, inductance is significantly higher than L1, L2 or the sum of L1 and L2. For example, when $L1 = L2 = Lx$, the effective inductance is almost $4 \cdot Lx$. This helps lower ripple current when the converter operates in a buck mode. In flyback or boost modes, only L1 is in the input conduction pathway so input switch A only sees L1, which is equal to Lx . This condition is beneficial, specifically to flyback mode, which enables a higher frequency operation. A lower inductance raises the current faster and the same level of stored energy inside the inductor core material is achieved sooner. Flyback or boost mode operation is usually needed when input voltage is lower than the output voltage or close to it. A higher frequency operation is better tolerated for the sake of parasitic capacitances operating at a lower voltage. Switch transition losses are low at lower input voltages. During buck mode the high inductance seen by the input pathway generated by L1 and L2 in series helps lower ripple current and reduces parasitic capacitance and switching losses. With the selection of different L1 and L2 values and proportions, very wide arbitrary voltage and current transfer ratios can be achieved with a small number of components, while switching loss can be kept at a minimum.

[0043] A third inductor, L3, on the same core can be added to generate an isolated output in either three or four switches configurations. A new actively controlled switch or diode is required to generate DC output in each case. Figures 5a and 5b show examples of an isolated inductor, L3. Figure 5a shows the circuit of Figure 1a with an additional inductor L3 and switch D to generate an isolated output. Figure 5b shows an isolated output version of Figure 3a with the addition of inductor L3 and switch E. This configuration has all of the benefits of a two coupled inductor version, along with having an isolated DC output.

[0044] Multiple stages of this novel converter can be daisy chained to similar stages or other standard DC-to-DC stages to achieve extended possibilities for power conversion. Single or coupled inductors in subsequent stages, or preceding stages, can be coupled to the same core as L1 and L2 (and L3 for isolated version) or be on discrete cores. Figures 6a and 6b illustrate examples of this multi-stage approach. In Figure 6a when switch B is turned on, or when switch D is turned on different return pathways for switch A are generated. When switch A closes current may pass through different windings on the same core, depending on the status of other switches, in this case switches B and D. Depending on L1, L2 and L3 values, and the duty cycles of switches A to E, different voltage or current transfer ratio can be generated. The presence of a new inductor on the same core, in this case L3, provides further possibilities for arbitrary transfer ratios without pushing frequency or duty cycles to extreme conditions. Figure

6b shows a version with (n) inductors on the same core and an expanded number of switches to create even more daisy chained stages.

[0045] One application of this novel converter is to drive a Light Emitting Diode (LED). An AC input has a variable voltage ranging from 0 to a peak positive voltage and then returning to zero followed by a negative voltage reaching a negative peak and then again returning to zero. This usually happens 50 or 60 times per second for conventional AC power sources in commercial and industrial use. This widely variable voltage makes designing a high efficiency AC-to-DC converter a challenge. LED strings sometimes have significant voltage drops across them. To maintain a good Power Factor it is required to drain power from the AC line in each cycle, the same as a resistive load.

[0046] A typical approach for AC-to-DC conversion is to use a Diode Bridge to convert input AC to a rectified DC voltage, and then use this DC voltage at the input of a DC-to-DC converter to generate proper output voltage. When input voltage is approximately higher than the LED string voltage drop, a step down regulator is required. When the input voltage is approximately lower than the LED string voltage drop, a step up regulator is required. The disclosed converter supports step down and step up operations.

[0047] It is desirable to eliminate or reduce AC line flicker effect created by variations in AC voltage. One common example of a flickering light is a florescent light. Florescent lamps operating on AC can generate double the frequency of the AC line driving them. In LED light driven by AC, usually a Diode Bridge rectifier generates an output with dominant frequency component of twice the AC line frequency. For example for a 60Hz AC line, a Diode Bridge rectifier generates an output with a dominant frequency of 120Hz. If there is no energy storage in the system, as the line voltage changes, light intensity may vary and generate a 120Hz flicker. Although humans cannot see light flickering at a frequency greater than 50 or so Hertz, the sensory system in some individuals can somehow detect the flicker. Ever since fluorescent lighting was introduced in workplaces, there have been complaints about headaches, eye strains and general eye discomforts.

[0048] The current invention has the ability to implement buck or boost operations. This shortens the duration of time power is not drained from the input. This reduces the amount of storage required to drive a LED during low momentary input voltages, referred to as a "transition period". Another approach used in the current invention is to drive an output load during a transition period using a series capacitor or super capacitor with the load. A simple boost or flyback stage can be connected to this capacitor and can use its energy to drive the LED when needed.

[0049] Figure 7a shows an LED string 700 with series storage capacitor, Cs. AC input is applied to a rectifier 702, which produces DC input, which is applied to DC-to-DC converter 704. The output of the DC-to-DC converter 704 is applied to the LED string 700. The capacitor Cs is in series with the LED string 700 and stores energy as current passes through the LED string 700. A controller 706 is connected to the input and output nodes of the capacitor Cs. The

controller 706 implements a boost or flyback conversion.

[0050] The controller 706 can be designed to use the stored energy of capacitor Cs during a transition period to drive the LED string 700. When received electrical energy from the AC line is high, energy is stored and this energy is used to drive the LED string 700 when received energy from the AC line is low. As the power from the DC-to-DC converter 704 increases, output current charges the LED string 700 and the series capacitor Cs. The LED string 700 voltage drop combined with the capacitor Cs voltage drop reduces the current generated by the DC-to-DC converter 704. The momentary power is fairly constant and $P=V*I$; where "P" is momentary power, "V" is output voltage and "I" is output current. For a certain packet of energy released to the output, an increase in the output voltage drop reduces the effective current. The series capacitor Cs stored energy can be calculated as $0.5*Cs*V^2$. Using this energy to drive the LED string 700 reduces the series capacitor voltage drop, which subsequently increases the effective switching DC-to-DC output current. With proper design, the voltage rating for this series capacitor (or super capacitor) can be lower, equal to or higher than the LED string 700 voltage drop. This approach simplifies the design for storage system required for flicker reduction.

[0051] Figure 7b shows the same stage with addition of a resistive component, Rs. Rs is a sense resistor that can be in series with the LED string 700 and Cs. Rs is a very low resistance to enable accurate monitoring of the LED string current and to enhance the accuracy of the flicker reduction stage.

[0052] Figure 8a illustrates an example AC-to-DC converter incorporating a three switch embodiment of the invention. AC input is applied to rectifier 800. A controller 802 modulates the switching of switches A, B and C. When rectified DC voltage from rectifier 800 is higher than the DC output, controller 802 configures switches A, B and C as follows. Switch A is the master toggling switch and switch C is in the opposite state of switch A, while switch B is off. This emulates a buck mode. Switch A turns on until current through Rs reaches a saturation current of L1 and L2 in series, then switch A turns off and switch C turns on until current that passes through L2 reaches zero. This initiates the next cycle of switch A activity.

[0053] When rectified DC voltage from the bridge rectifier 800 is lower than $(L1 / (L1 + L2)) * DC\ out$, the controller 802 configures switch A to be on, switch B is the master toggling switch and switch C is the inverse of switch B. This provides a boost equivalent conversion. Switch B turns on until current in Rs reaches L1 saturation current, then it turns off until current that passes L1 and L2 in series reaches zero.

[0054] When rectified DC voltage from bridge rectifier 800 is between $(L1 / (L1 + L2)) * DC\ out$ and DC out, the controller 802 configures the switches as follows. Switch A is the master toggling switch, switch B is on and switch C is in the inverse state of switch A. As described before, this emulates a flyback conversion with one common input, output line. Switch A turns on until current in Rs reaches L1 saturation current, then it turns off until current that passes through L2 reaches zero. In Figure 8a, capacitor Cout is optionally added to DC Out to reduce

output ripple voltage. An output capacitor of this type may also be used with other embodiments of the invention.

[0055] Figure 8b illustrates a similar circuit with four switches. The controller 802 only controls switches A and B. Switch C and switch D are diodes. This controller, like the other controllers of the invention, can implement three modes: buck, flyback and boost.

[0056] Those skilled in the art will appreciate that the relatively simple circuit of the invention supports buck, flyback and boost modes of operation with as few as two active switches. This facilitates lower component costs, smaller sizes and ease of manufacturing. Advantageously, the duty cycle transitions between modes of operation are relatively small, thereby reducing power losses. For example, an input voltage span of $36\times$ (input voltage in the range of $V_{out}/6$ to $V_{out}\times 6$) can be supported by a range of duty cycles that never falls below 25%. In a flyback converter with a 1-to-1 ratio, over the same $36\times$ input voltage span, the duty cycle drops to as low as 2.7%, resulting in large power losses. Thus, the invention provides a 9.25x enhancement in duty cycle efficiency compared to a prior art flyback converter.

[0057] The invention supports a switching frequency with a period of $100\times(t_{FALL}+t_{RISE})$, while still maintaining an efficiency higher than 95% over a $9\times$ input voltage change (for example $V_{out}/3$ to $V_{out}\times 3$). For a typical switch with 10nS fall and rise time, this can amount to a 500KHz switching speed. Advantageously, the configuration of the circuit of the invention allows inductor cores as small as 0.25cc to be used to convert in excess of 50W.

[0058] Beside LED drivers, this invention can be used in any environment with a wide varying voltage, AC or DC. Examples of such applications are AC-to-DC or DC-to-DC converters for telecommunication equipment driving power from noisy lines, battery operated devices, such as notebook computers and handheld devices, or power supplies on automotive, train, boat, airplane and other vehicles.

[0059] Another application for this invention is any isolated AC-to-DC or DC-to-DC power supply. This includes but is not limited to, portable power supplies, portable computer power supplies and server computer power supplies.

[0060] The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that specific details are not required in order to practice the invention. Thus, the foregoing descriptions of specific embodiments of the invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed; obviously, many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, they thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the following claims and their equivalents define the scope of the invention.

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US20040070376A1 [0006]
- US2008100273A1 [0007]

Patentkrav**1.** DC-til-DC-omformer omfattende:

- 5 et DC-input (IN) omfattende en positiv inputterminal og en negativ inputterminal
- et DC-output (OUT) omfattende en positiv outputterminal og en negativ outputterminal,
- to eller flere induktorer (L1, L2) koblet til en fælles kerne;
- tre omskiftere (A, B, C), der inkluderer to eller flere aktive omskiftere,
- 10 en kontroller konfigureret til at styre drift af DC-til-DC-omformeren ved at styre de aktive omskiftere
- en positiv inputgren, en negativ inputgren, en positiv outputgren, en negativ outputgren og en intern gren,
- og en positiv intern knude og en negativ intern knude;
- 15 hvor: den positive inputgren er forbundet mellem den positive inputterminal og den positive interne knude;
- den negative inputgren er forbundet mellem den negative inputterminal og den negative interne knude;
- den interne gren er forbundet mellem den positive interne knude og den negative interne knude;
- 20 den positive outputgren er forbundet mellem den positive interne knude og den positive outputterminal;
- den negative outputgren er forbundet mellem den negative interne knude og den negative outputterminal;

hvor: den første af de mindst to koblede induktorer (L1) er placeret i serie med DC-inputtet (IN), enten i den positive inputgren eller i den negative inputgren;

5 den anden af de mindst to koblede induktorer (L2) er placeret i serie med DC-outputtet (OUT), enten i den positive eller i den negative outputgren;

den første af de mindst to aktive omskiftere (A) er placeret i serie med DC-inputtet (IN), enten i den positive inputgren eller i den negative inputgren

den interne gren består af den anden af de mindst to aktive omskiftere (B);

10 og den resterende tredje omskifter (C) er placeret i serie med DC-outputtet (OUT), enten i den positive outputgren eller i den negative outputgren;

kendetegnet ved at kontrolleren er yderligere konfigureret til at vælge en DC-DC-topologi blandt et sæt af mere end én mulige DC-DC-topologier baseret på inputspændingen af DC-inputtet (IN), ved at styre de mindst to aktive omskiftere, således at én af de tre omskiftere tvinges til at lede strøm permanent i henhold til den valgte topologi, så længe den valgte topologi ikke ændres, de resterende to omskiftere tvinges til vekslende at lede strøm på en komplementerende måde, således at det samlede antal af induktorer, der leder strøm, er vekselvist ændret og DC-DC-strømomformningen udføres i henhold til den valgte topologi.

20

2. DC-til-DC-omformeren ifølge krav 1 konfigureret til at udføre DC-DC-strømomformning i henhold til en boost-funktion, når den første aktive omskifter (A) er permanent tændt.

25 **3.** DC-til-DC-omformeren ifølge krav 1 konfigureret til at udføre DC-DC-strømomformning i henhold til en retur-funktion, når den tredje omskifter (C) holdes tændt eller når den er en diode og kontrolleren er konfigureret til at drive de andre to aktive omskiftere (A, B) for at tænde og slukke dem på en komplementerende måde.

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- 4.** DC-til-DC-omformeren ifølge krav 1 konfigureret til at udføre DC-DC-strømomformning i henhold til en tilbageløbs-funktion, når den anden aktive omskifter (B) er permanent tændt.
- 5 **5.** DC-til-DC-omformeren ifølge krav 1, hvor den tredje omskifter er en diode (C).
- 6.** DC-til-DC-omformeren ifølge krav 1, hvor kontrolleren er konfigureret til at overvåge inputbelastningsegenskaber ved at overvåge elektriske egenskaber af inputomskifteren.
- 10 **7.** DC-til-DC-omformeren ifølge krav 1, hvor kontrolleren er konfigureret til at overvåge outputbelastningsegenskaber ved at overvåge elektriske egenskaber af mindst en omskifter.
- 15 **8.** DC-til-DC-omformeren ifølge krav 1 yderligere omfattende en keramisk kondensator ved outputknuden.
- 9.** DC-til-DC-omformeren ifølge krav 1, hvor kontrolleren er konfigureret til kun at anvende driftsperioder på 25 % eller mere.
- 20 **10.** DC-til-DC-omformer omfattende:
- et DC-input (IN) omfattende en positiv inputterminal og en negativ inputterminal;
 - et DC-output (OUT) omfattende en positiv outputterminal og en negativ outputterminal,
 - to eller flere induktorer (L1, L2) koblet til en fælles kerne;
 - fire omskiftere (A, B, C, D), der inkluderer to eller flere aktive omskiftere,
- 25

og en kontroller konfigureret til at styre drift af DC-til-DC-omformeren ved at styre de aktive omskiftere for at vælge en DC-DC-topologi blandt et sæt af mere end én mulige DC-DC-topologier baseret på inputspændingen af DC-inputtet (IN);

- 5 en positiv inputgren, en negativ inputgren, en positiv outputgren, en negativ outputgren, en positiv intern gren, en negativ intern gren, en første parallel intern gren og en anden parallel intern gren

og en første positiv intern knude, en anden positiv intern knude, en første negativ intern knude og en anden negativ intern knude;

- 10 hvor: den positive inputgren er forbundet mellem den positive inputterminal og den første positive interne knude;

den negative inputgren er forbundet mellem den negative inputterminal og den første negative interne knude;

- 15 den første parallelle interne gren er forbundet mellem den første positive interne knude og den første negative interne knude;

den positive interne gren er forbundet mellem den første positive interne knude og den anden positive interne knude;

den negative interne gren er forbundet mellem den første negative interne knude og den anden negative interne knude;

- 20 den anden parallelle interne gren er forbundet mellem den anden positive interne knude og den anden negative interne knude;

den positive outputgren er forbundet mellem den anden positive interne knude og den positive outputterminal;

- 25 og den negative outputgren er forbundet mellem den anden negative interne knude og den negative outputterminal;

hvor: den første af de mindst to koblede induktorer (L1) er placeret i serie med DC-inputtet (IN), enten i den positive inputgren eller i den negative inputgren;

den anden af de mindst to koblede induktorer (L2) er placeret i serie med DC-outputtet (OUT), enten i den positive eller i den negative outputgren;

den første af de mindst to aktive omskiftere (A) er placeret i serie med DC-inputtet (IN), i den positive inputgren;

5 den første parallelle interne gren består af den anden af de mindst to aktive omskiftere (B);

den tredje omskifter (C) er placeret enten i den positive interne gren eller i den negative interne gren;

og den anden parallelle interne gren består af den fjerde omskifter (D);

10 hvor, ved at styre de to til fire aktive omskiftere, kontrolleren er konfigureret til permanent at tvinge en af omskifterne til at lede strøm permanent i henhold til den valgte topologi, så længe den valgte topologi ikke ændres, således at:

15 - driften af DC-til-DC-omformeren er i henhold til en boost-funktion, når den første aktive omskifter (A) tvinges permanent tændt og de resterende aktive omskiftere styres, således at den anden aktive omskifter (B) og den tredje omskifter (C) vekslende leder strøm på en komplementerende måde;

20 - driften af DC-til-DC-omformeren er i henhold til en tilbageløbs-funktion, når den anden aktive omskifter (B) tvinges permanent tændt og de resterende aktive omskiftere styres, således at den første aktive omskifter (A) og den fjerde omskifter (D) vekslende leder strøm på en komplementerende måde;

25 - driften af DC-til-DC-omformeren er i henhold til en retur-funktion, når den tredje omskifter (C) er en aktiv omskifter og tvinges permanent tændt og de resterende aktive omskiftere styres, således at den første aktive omskifter (A) og den fjerde omskifter (D) vekslende leder strøm på en komplementerende måde eller når den tredje omskifter er en diode og de resterende aktive omskiftere styres, således at den første aktive omskifter (A) og den fjerde
30

omskifter (D) vekslende leder strøm på en komplementerende måde.

11. DC-til-DC-omformeren ifølge krav 10, hvor mindst en af den tredje og fjerde omskifter er en diode (C, D).

12. DC-til-DC-omformeren ifølge krav 10, hvor kontrolleren er konfigureret til at overvåge inputbelastningsegenskaber ved at overvåge elektriske egenskaber af inputomskifteren.

10

13. DC-til-DC-omformeren ifølge krav 10, hvor kontrolleren er konfigureret til at overvåge outputbelastningsegenskaber ved at overvåge elektriske egenskaber af mindst en omskifter.

DRAWINGS

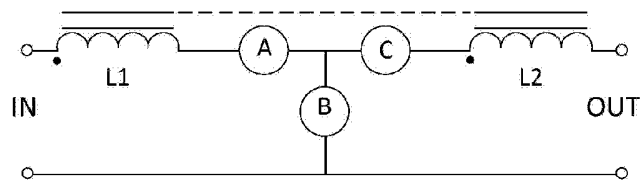


Figure 1a

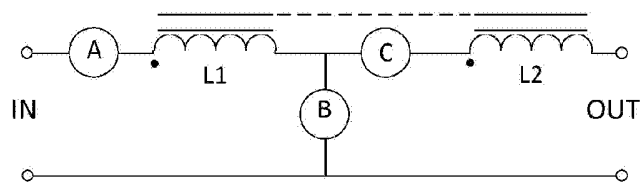


Figure 1b

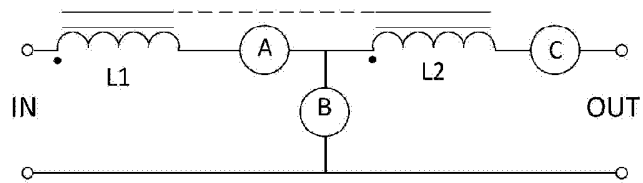


Figure 1c

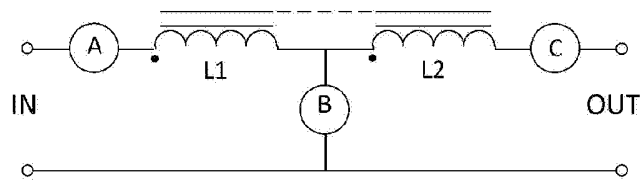


Figure 1d

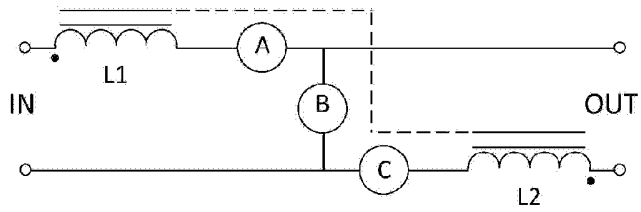


Figure 1e

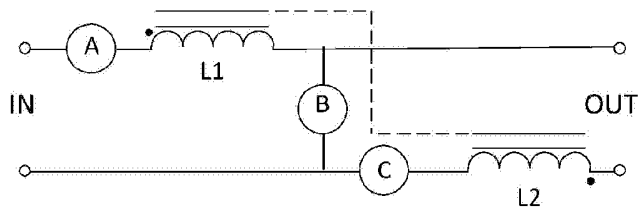


Figure 1f

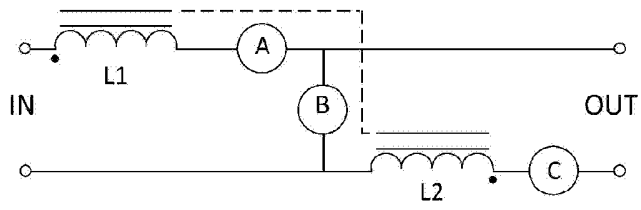


Figure 1g

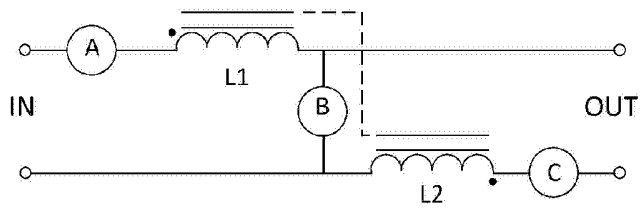


Figure 1h

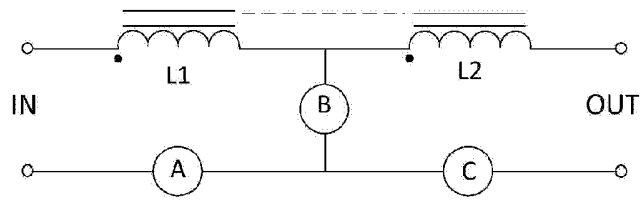


Figure 1i

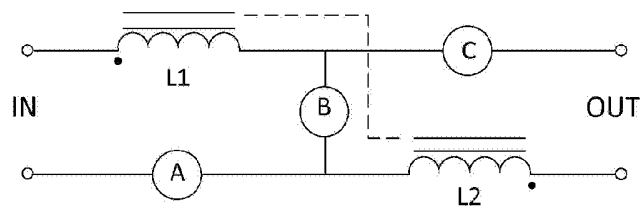


Figure 1j

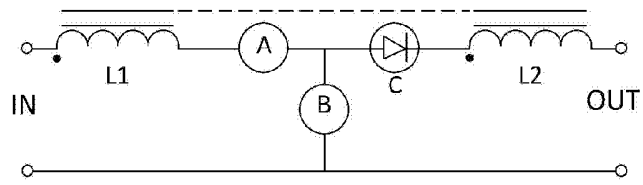


Figure 2a

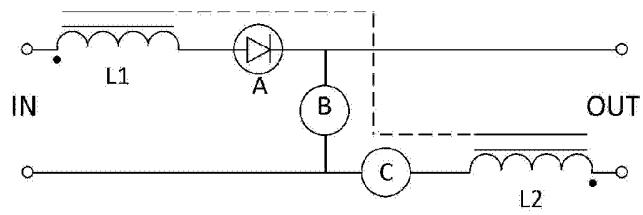


Figure 2b

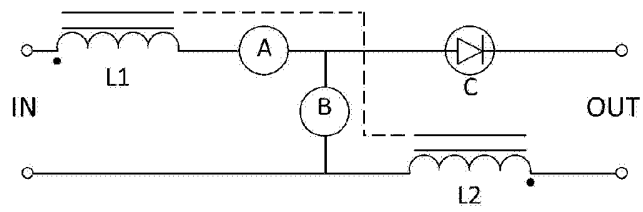


Figure 2c

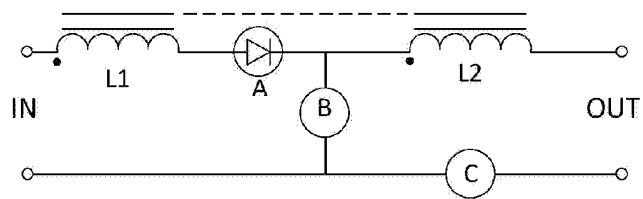


Figure 2d

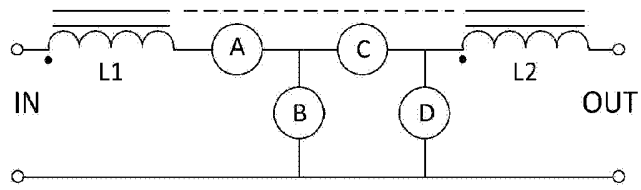


Figure 3a

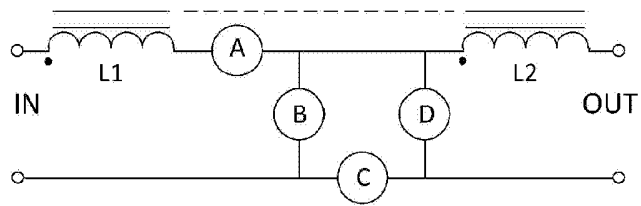


Figure 3b

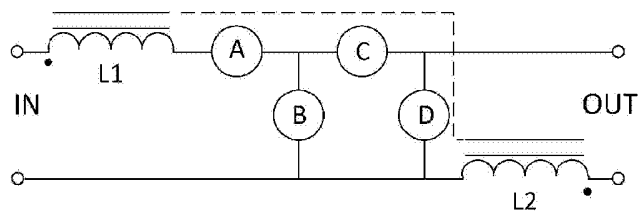


Figure 3c

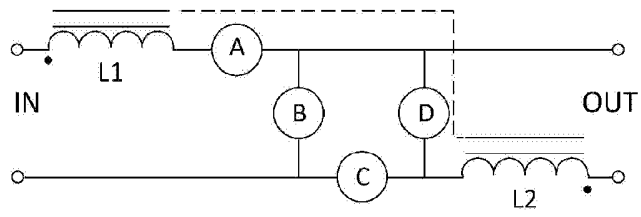


Figure 3d

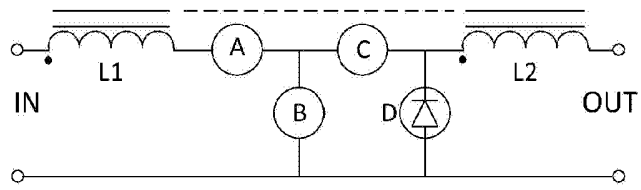


Figure 4a

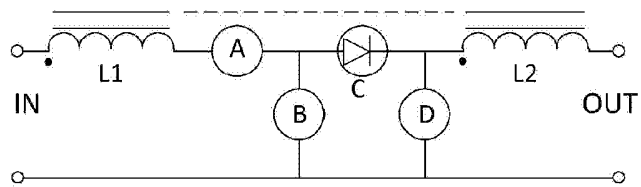


Figure 4b

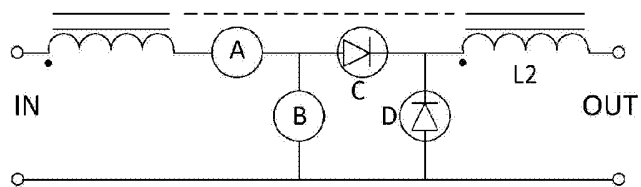


Figure 4c

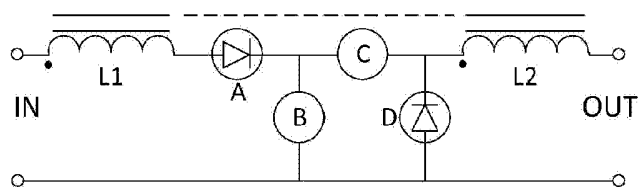


Figure 4d

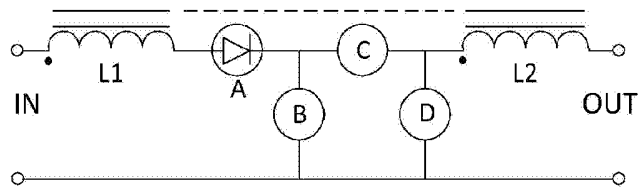


Figure 4e

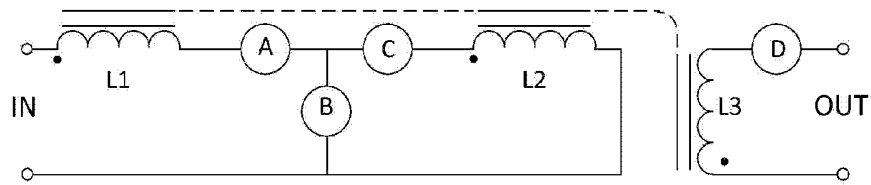


Figure 5a

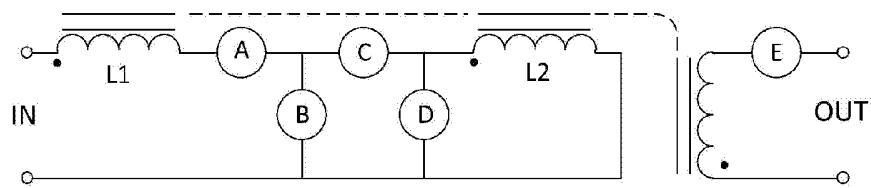


Figure 5b

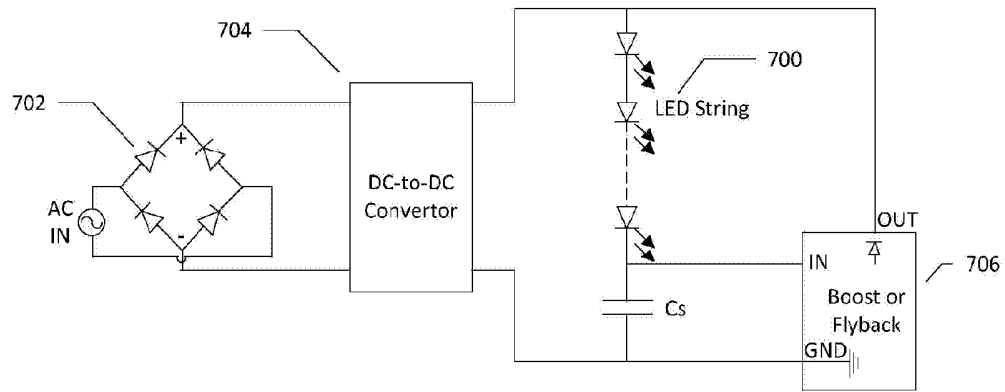


Figure 7a

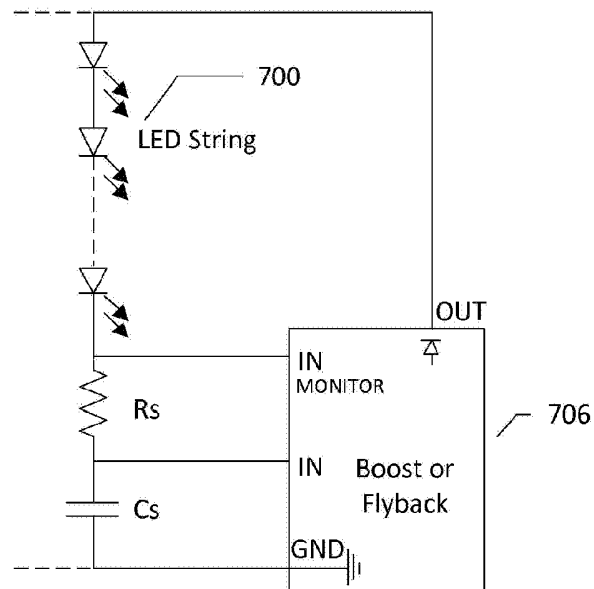


Figure 7b

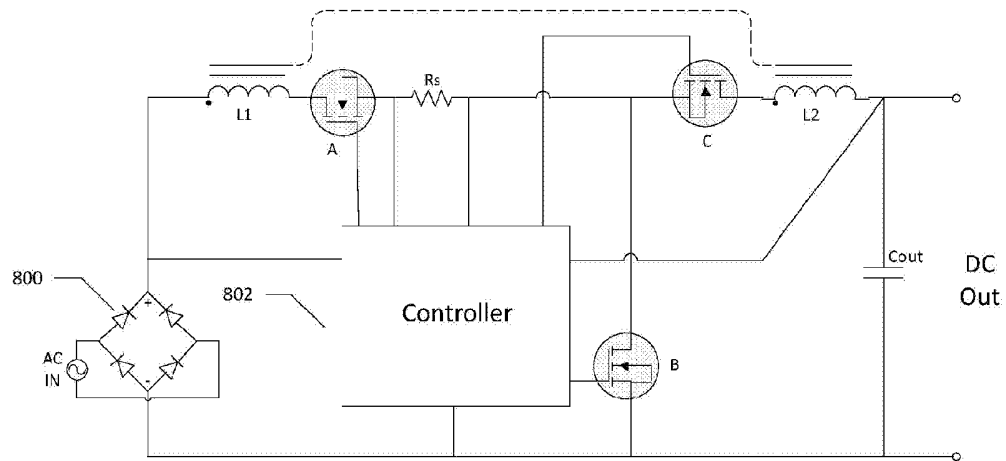


Figure 8a

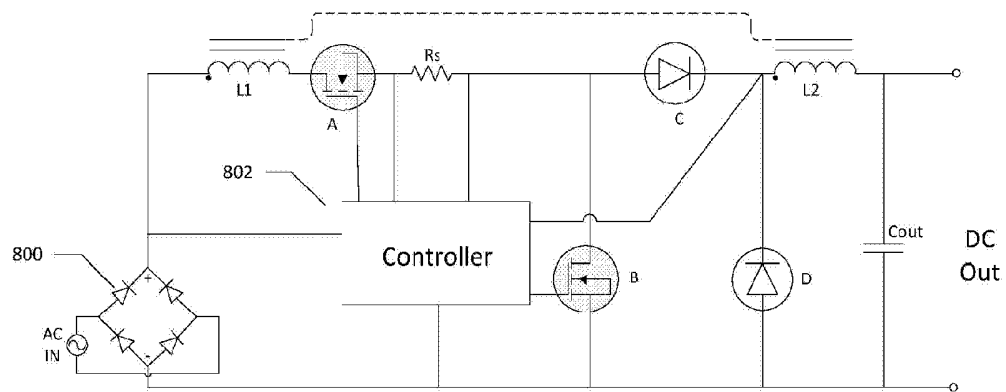


Figure 8b