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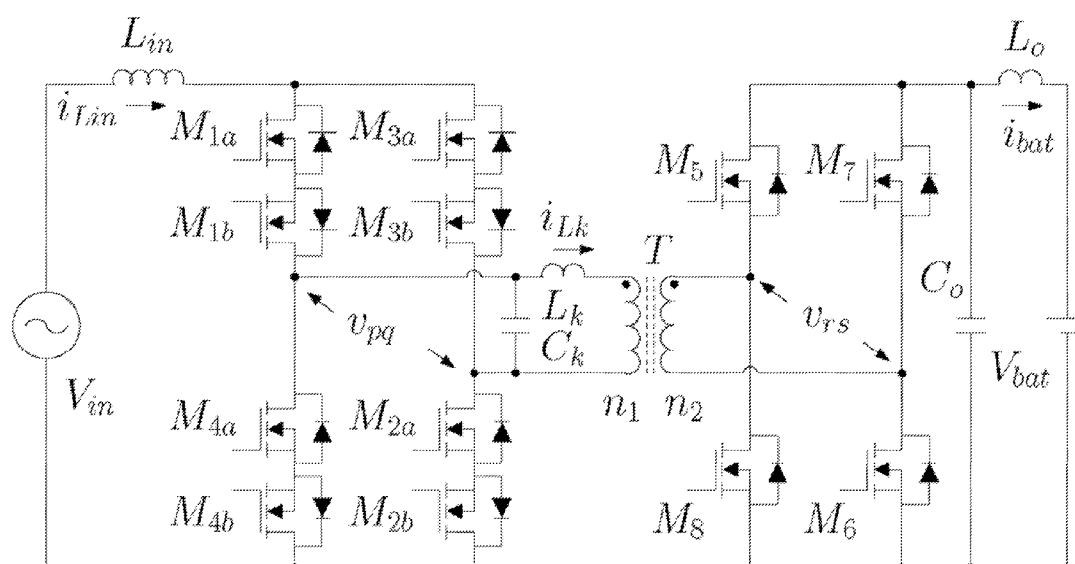
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(54) Title: SINGLE PHASE SINGLE STAGE BI-DIRECTIONAL LEVEL 1 ELECTRIC VEHICLE BATTERY CHARGER

FIG. 1



(57) **Abstract:** A single phase single stage level-1 electric vehicle (EV) battery charger can control the power flow in both directions. The converter efficiency is high as the devices undergo ZCS which reduces switching loss in the devices. This converter does not require any intermediate DC link capacitor stage and the power density of the converter is high.

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SINGLE PHASE SINGLE STAGE BI-DIRECTIONAL LEVEL 1 ELECTRIC VEHICLE BATTERY CHARGER

BACKGROUND

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/546,955, entitled “Single Phase Single Stage Bi-Directional Level 1 Electric Vehicle Battery Charger,” filed August 17, 2017, the entire contents of which are hereby incorporated by reference.

[0002] This disclosure pertains to an electric vehicle (EV) battery charging application.

[0003] The electrification of transportation has significantly increased in recent times to reduce fossil fuel consumption and greenhouse emissions. Electric vehicles (EVs) are gradually replacing the conventional internal combustion engine based vehicles. However, the increasing penetration of these EVs can have a considerable impact on the grid. Thus the chargers used for charging the batteries should have additional features like power factor correction (PFC) controllers and bidirectional power flow capabilities to minimize the impact of power quality on the grid.

[0004] Commercially available single-phase isolated AC-DC EV battery chargers can be classified into two-stage solution and single-stage solution. The two stage solution consists of a front-end PFC stage. It is followed by an isolated DC-DC stage. The frontend stage employs diode bridge rectifiers followed by a boost, buck, or buck–boost stages. Large storage elements like electrolytic capacitors are required to link these two stages. The main advantage of this two-stage solution is that the output voltage regulation and PFC control are decoupled. Thus, the PFC performance can always be ensured despite the change in input AC voltage and load power. This PFC operation enhances the power quality of the grid. Nevertheless, this two-stage solution suffers from low overall efficiency due to more number of devices. Moreover, the converter power density is limited because of the two separate stages and bulky DC link capacitors.

[0005] The alternative solution is to develop single stage AC-DC converters. The fly back converters are selected to achieve cost-effective designs because theoretically only one active switch is necessary. However, they are only suitable for lower power level because

of the high-voltage and current stresses on the devices. For high-power rating single stage AC-DC converters, full bridge (FB) type topologies are preferred. In the resonant type FB and dual active bridge type FB AC-DC converters, the output voltage regulation is realized either by changing the switching frequency or by shifting the phase angle between the two bridges. These converters only use capacitors as the output filter. Thus, the voltage rating of the capacitors is lower. However, the main disadvantage of these converters is the nonlinear relation between the control parameters and the input current. Even if a complex control algorithm is applied, the grid current total harmonics distortion (THD) is large compared to conventional two-stage solution.

SUMMARY

[0006] The present disclosure relates generally to a battery charger for electric vehicles (EVs), and particularly to a single stage single phase power converter for EV charging application.

[0007] In preferred embodiments, the AC side of the proposed converter has a current-fed full bridge matrix converter that is connected to another full-bridge converter on a secondary side of a high-frequency (HF) transformer. The advantages of the proposed EV charger are its bidirectional power flow capabilities, inherent power factor correction (PFC) control, the fact that intermediate DC link capacitors are not required, soft switching capabilities in both primary and secondary side switches, improved grid current quality due to input line inductor, and the fact that the power density and efficiency of the converter is high.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 shows converter topology for a preferred embodiment of a single phase, single stage level-1 bidirectional electric vehicle (EV) charger.

[0009] FIG. 2 shows a preferred embodiment of a converter in Mode 1 of operation during grid to vehicle (G2V) mode.

[0010] FIG. 3 shows a preferred embodiment of a converter in Mode 2 of operation during G2V mode.

[0011] FIG. 4 shows a preferred embodiment of a converter in Mode 3 of operation during G2V mode.

[0012] FIG. 5 shows a preferred embodiment of a converter in Mode 4 of operation during G2V mode.

[0013] FIG. 6 shows a preferred embodiment of a converter in Mode 9 of operation during vehicle to grid (V2G) mode.

[0014] FIG. 7 shows a preferred embodiment of a converter in Mode 10 of operation during V2G mode.

[0015] FIG. 8 shows a preferred embodiment of a converter in Mode 11 of operation during V2G mode.

[0016] FIG. 9 shows a preferred embodiment of a converter in Mode 12 of operation during V2G mode.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0017] The present disclosure relates to a single phase, single stage level-1 electric vehicle (EV) charger. The single phase single stage level-1 EV battery charger can control the power flow in both directions. Preferred switching sequences of the devices are also described. The converter efficiency is high as the devices undergo ZCS which reduces switching loss in the devices. This converter does not require any intermediate DC link capacitor stage. As an advantage, the power density of the converter is high.

[0018] FIG. 1 shows converter topology for a preferred embodiment of a single phase, single stage level-1 bidirectional electric vehicle (EV) charger having inherent PFC control. The primary AC side includes 8 silicon carbide (SiC) metal–oxide–semiconductor field-effect transistors (MOSFETs) labeled M_{1a} to M_{4b} and the secondary side includes 4 SiC MOSFETs labeled M_5 to M_8 . The converter develops a high frequency AC in the primary side of the isolating transformer, operating as a cycloconverter. It is then rectified in the secondary side to generate DC voltage. Similar operation is conducted in reverse direction for reverse power flow. Zero current switching (ZCS) is achieved with the help of a resonating circuit that includes leakage inductance (L_k) of the transformer and an external capacitor (C_k).

[0019] The converter topology shown in FIG. 1 is a preferred embodiment that can be extended to various applications. The proposed topology can be extended for grid integration of photovoltaic cells. It can operate independently in both grid connected mode and islanded mode. The proposed EV charger topology can also be extended for bidirectional power flow with a three phase operation.

[0020] FIG. 2 shows a preferred embodiment of a converter during mode of operation that is grid to vehicle (G2V) mode. In this mode, which may be referred to as Mode 1, power is transferred from the input source (V_{in}) to the battery (V_{bat}). For G2V operation, active switching is conducted in the primary side and the secondary side devices are operated as a diode bridge rectifier. For positive input voltage ($V_{in} > 0$), the operation can be divided from Mode 1 to Mode 4. Similarly, the operation can be divided from Mode 5 to Mode 8 for $V_{in} < 0$. In this mode M_{1a} , M_{2a} are kept on and M_{1b} and M_{2b} are kept off. As a result, the input current flows from the source (V_{in}) to leakage inductor (L_k) and capacitor (C_k) through M_{1a} , M_{2a} and diodes of M_{1b} and M_{2b} . In the secondary side, diodes of M_5 and M_6 conduct to charge the battery (V_{bat}).

[0021] FIG. 3 shows a preferred embodiment of a converter in Mode 2 of G2V mode. In Mode 2, Device M_{4a} is turned on and then M_{2a} is turned off. As a result, ZCS occurs for M_{2a} . In this case, the input current (I_{in}) freewheels through M_{1a} , M_{4a} and diodes of M_{1b} and M_{4b} . The capacitor C_k and inductor L_k starts resonating. This resonance causes the leakage current through L_k to reach input current level. As a result, a voltage spike does not appear across the primary device. In other words, the C_k acts as a snubber capacitor. It helps in arresting the voltage overshoot caused due to the current mismatch between the leakage inductor and line inductor. At the end of Mode 2, M_{3a} is turned on. It exhibits ZCS turn-on.

[0022] FIG. 4 shows a preferred embodiment of a converter in Mode 3 during G2V mode. In Mode 3, M_{1a} is turned off. The input current flows through M_{3a} , M_{4a} and diodes of M_{3b} and M_{4b} . The current direction reverses in the leakage inductor L_k and C_k . In the secondary side, diodes of M_7 and M_8 conduct to charge the battery (V_{bat}).

[0023] FIG. 5 shows a preferred embodiment of a converter in Mode 4 during G2V mode. In this mode, M_{2a} is turned on and then M_{4a} is turned off. As a result M_{4a} experiences ZCS turn-off. In this case, the input current (I_{in}) freewheels through M_{3a} and M_{2a} . The capacitor C_k and inductor L_k starts resonating. This resonance causes the leakage current through L_k to reach input current level similar to Mode 2. As a result, a voltage spike does not appear across the primary device. This helps in arresting the voltage overshoot caused due to the current mismatch between the leakage inductor and line inductor. At the end of Mode 3, M_{1a} is turned on. It exhibits ZCS turn-on.

[0024] During $V_{in} > 0$, M_{1a} , M_{2a} , M_{3a} and M_{4a} exhibit ZCS. In a similar fashion, Mode 5 to Mode 8 can also be explained. Here M_{1b} , M_{2b} , M_{3b} and M_{4b} exhibit ZCS. It is important to notice that C_k continues to conduct current even if $V_{bat} > V_{in}$. As a result, there is a path for the input current to flow at every switching condition. This phenomena ensures PFC for all loading conditions.

[0025] In vehicle to grid (V2G) mode, power is transferred from the battery (V_{bat}) to the grid (V_{in}). For V2G operation, battery side devices are switched in square wave mode and three level sine triangle pulse-width modulation (PWM) switching is conducted for the grid side devices. For positive input voltage ($V_{in} > 0$), the operation can be divided from Mode 9 to Mode 12. Similarly, the operation can be divided from Mode 13 to Mode 16 for $V_{in} < 0$. For V2G operation, the resonating capacitor C_k is removed from the circuit through a contactor.

[0026] FIG. 6 shows a preferred embodiment of a converter in Mode 9 during V2G mode. In this mode, M_5 and M_6 in the secondary side are kept on. The grid current flows through M_{1b} , M_{2b} and diodes of M_{1a} and M_{2a} .

[0027] FIG. 7 shows a preferred embodiment of a converter in Mode 10 during V2G mode. In Mode 10, M_{4b} is turned on. As a result, the grid current freewheels through M_{4b} , M_{1b} and diodes of M_{1a} and M_{4a} . M_{2b} is turned off once the grid current is completely transferred to the freewheeling branch exhibiting ZCS turn-off. At the end of this mode M_{3b} is turned on. M_{3b} experiences ZCS turn on as there is no current through it.

[0028] FIG. 8 shows a preferred embodiment of a converter in Mode 11 during V2G mode. In Mode 11, M_{1b} is turned off. As a consequence, grid current flows through M_{4b} , M_{3b} and diodes of M_{4a} and M_{3a} respectively. This switching cycle reverses the direction of current flowing through the leakage inductor (L_k).

[0029] FIG. 9 shows a preferred embodiment of a converter in Mode 12 during V2G mode. At the end of mode 11, M_{2b} is turned on again. The grid current again freewheels through M_{2b} , M_{3b} and diodes of M_{2a} and M_{3a} . After the transfer of grid current to the freewheeling branch, M_{4b} is turned off. It exhibits ZCS turn-off.

[0030] Mode 9 to Mode 12 are continued until M_5 and M_6 are in the on-state in the secondary side. Once M_7 and M_8 are turned on, the switching cycles described above are reversed. In a similar fashion, the switching of the devices are carried out for $V_{in} < 0$. As described above, all devices on the primary side undergo ZCS.

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WHAT IS CLAIMED IS:

1. A power converter having bidirectional power flow capabilities and inherent power factor correction (PFC) control, comprising:

a high frequency transformer comprising a primary AC side, a secondary side, and a resonating circuit,

wherein the primary AC side of the high frequency transformer comprises a current-fed full bridge matrix converter, wherein the current-fed full bridge matrix converter comprises eight silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) positioned in four pairs, wherein a first pair of SiC MOSFETs consists of a first A SiC MOSFET and a first B SiC MOSFET, wherein a second pair of SiC MOSFETs consists of a second A SiC MOSFET and a second B SiC MOSFET, wherein a third pair of SiC MOSFETs consists of a third A SiC MOSFET and a third B SiC MOSFET, and wherein a fourth pair of SiC MOSFETs consists of a fourth A SiC MOSFET and a fourth B SiC MOSFET,

wherein the secondary side of the high frequency transformer comprises a full bridge matrix converter, wherein the full bridge matrix converter comprises four SiC MOSFETs, wherein the four SiC MOSFETs consist of a fifth SiC MOSFET, a sixth SiC MOSFET, a seventh SiC MOSFET, and an eighth SiC MOSFET, and

wherein the resonating circuit comprises a leakage inductor of the high frequency transformer and a capacitor.

2. An electric vehicle (EV) battery charger comprising the power converter of claim 1.

3. The electric vehicle (EV) battery charger of claim 2, further comprising an input source and a battery.

4. One or more photovoltaic cells comprising the power converter of claim 1.

5. A method for charging an electric vehicle (EV) battery in grid to vehicle mode, comprising:

transferring input current from an input source to the power converter of claim 1;

performing active switching in the primary AC side of the of the high frequency transformer by turning on the first A SiC MOSFET and the second A SiC MOSFET and turning off or keeping off the first B SiC MOSFET and the second B SiC MOSFET, whereby the first B SiC MOSFET and the second B SiC MOSFET acts as diodes, and whereby the input current flows from the input source to the leakage inductor and the capacitor through the first A SiC MOSFET and the second A SiC MOSFET and the diodes of the first B SiC MOSFET and the second B SiC MOSFET; and

charging the battery by conducting current through the fifth SiC MOSFET and the sixth SiC MOSFET, which act as diodes.

6. The method of claim 5, further comprising the steps of:

performing active switching in the primary AC side of the high frequency transformer by turning on the fourth A SiC MOSFET and turning off the second A SiC MOSFET, whereby the first B SiC MOSFET and the fourth B SiC MOSFET acts as diodes, whereby the input current flows through the first A SiC MOSFET and the fourth A SiC MOSFET and the diodes of the first B SiC MOSFET and the fourth B SiC MOSFET, and whereby the capacitor resonates to cause leakage current through the leakage inductor to reach input current level; and

performing active switching in the primary AC side of the high frequency transformer by turning on the third A SiC MOSFET, whereby the third A SiC MOSFET exhibits zero current switching turn-on.

7. The method of claim 6, further comprising the steps of:

performing active switching in the primary AC side of the of the high frequency transformer by turning off the first A SiC MOSFET, whereby the third B SiC MOSFET and the fourth B SiC MOSFET act as diodes, and whereby the input current flows to the leakage inductor

and the capacitor through the third A SiC MOSFET and the fourth A SiC MOSFET and the diodes of the third B SiC MOSFET and the fourth B SiC MOSFET; and

charging the battery by conducting current through the seventh SiC MOSFET and the eighth SiC MOSFET, which act as diodes.

8. The method of claim 7, further comprising the steps of:

performing active switching in the primary AC side of the high frequency transformer by turning on the second A SiC MOSFET and turning off the fourth A SiC MOSFET, whereby the fourth A SiC MOSFET exhibits zero current switching turn-off, whereby the third B SiC MOSFET and the second B SiC MOSFET act as diodes, whereby the input current flows through the third A SiC MOSFET and the second A SiC MOSFET and the diodes of the third B SiC MOSFET and the second B SiC MOSFET, and whereby the capacitor resonates to cause leakage current through the leakage inductor to reach input current level; and

performing active switching in the primary AC side of the high frequency transformer by turning on the first A SiC MOSFET, whereby the first A SiC MOSFET exhibits zero current switching turn-on.

9. A method for operating an electric vehicle (EV) battery in vehicle to grid mode, comprising:

transferring power from the battery to the secondary side of the power converter of claim 1;

performing active switching in the secondary side of the high frequency transformer in square wave mode by turning on or keeping on the fifth SiC MOSFET and the sixth SiC MOSFET; and

performing active switching in the primary AC side of the of the high frequency transformer through three level sine triangle pulse-width modulation (PWM) switching by turning on the first B SiC MOSFET and the second B SiC MOSFET and turning off or keeping off the first

A SiC MOSFET and the second A SiC MOSFET, whereby the first A SiC MOSFET and the second A SiC MOSFET acts as diodes, and whereby grid current flows through the first B SiC MOSFET and the second B SiC MOSFET and the diodes of the first A SiC MOSFET and the second A SiC MOSFET.

10. The method of claim 9, further comprising the steps of:
 - performing active switching in the primary AC side of the high frequency transformer by turning on the fourth B SiC MOSFET, whereby the first A SiC MOSFET and the fourth A SiC MOSFET acts as diodes, whereby the grid current flows through the first B SiC MOSFET and the fourth B SiC MOSFET and diodes of the first A SiC MOSFET and the fourth A SiC MOSFET;
 - performing active switching in the primary AC side of the high frequency transformer by turning off the second B SiC MOSFET after the grid current is completely transferred, whereby the second B SiC MOSFET exhibits zero current switching turn-off; and
 - performing active switching in the primary AC side of the high frequency transformer by turning on the third B SiC MOSFET, whereby the third B SiC MOSFET exhibits zero current switching turn-on.
11. The method of claim 10, further comprising the steps of:
 - performing active switching in the primary AC side of the of the high frequency transformer by turning off the first B SiC MOSFET, whereby the grid current flows through the fourth B SiC MOSFET and the third B SiC MOSFET and diodes of the fourth A SiC MOSFET and the third A SiC MOSFET, whereby the direction of current flowing through the leakage inductor is reversed.
12. The method of claim 11, further comprising the steps of:
 - performing active switching in the primary AC side of the high frequency transformer by turning on the second B SiC MOSFET, whereby the

grid current flows through the second B SiC MOSFET and the third B SiC MOSFET and diodes of the second A SiC MOSFET and the third A SiC MOSFET; and

performing active switching in the primary AC side of the high frequency transformer by turning off the fourth B SiC MOSFET after the grid current is completely transferred, whereby the fourth B SiC MOSFET exhibits zero current switching turn-off.

FIG. 1

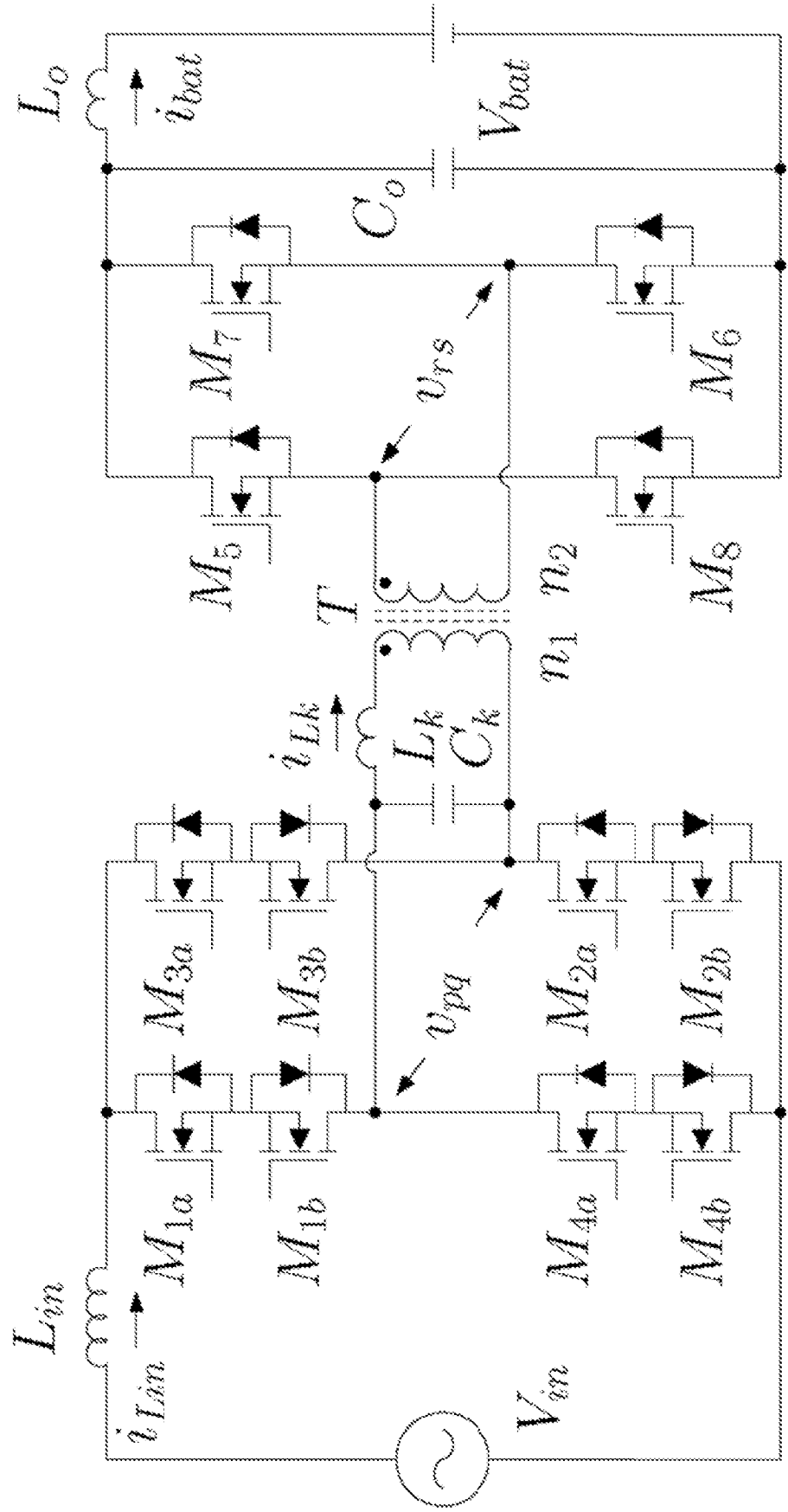


FIG. 2

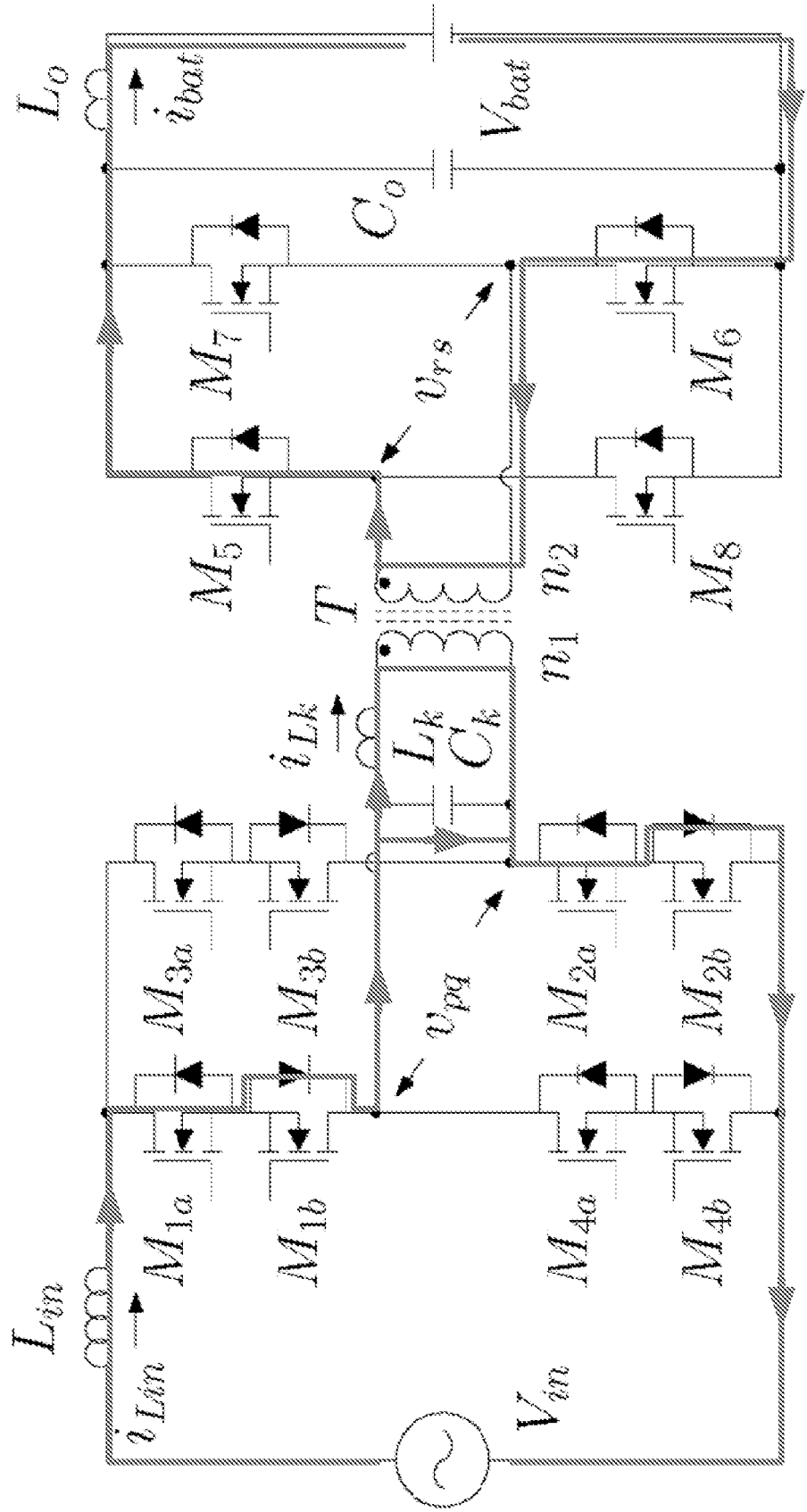


FIG. 3

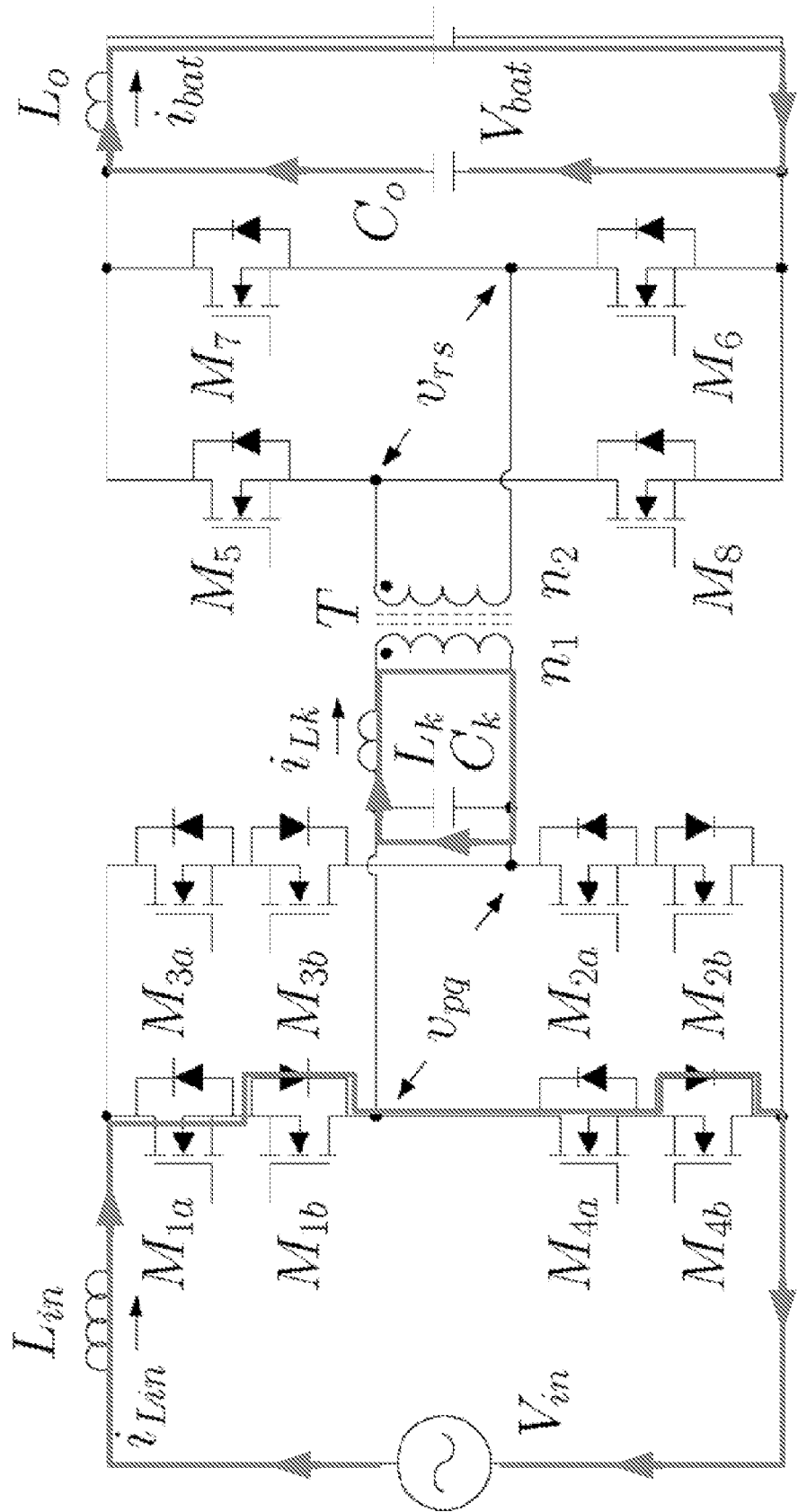


FIG. 4

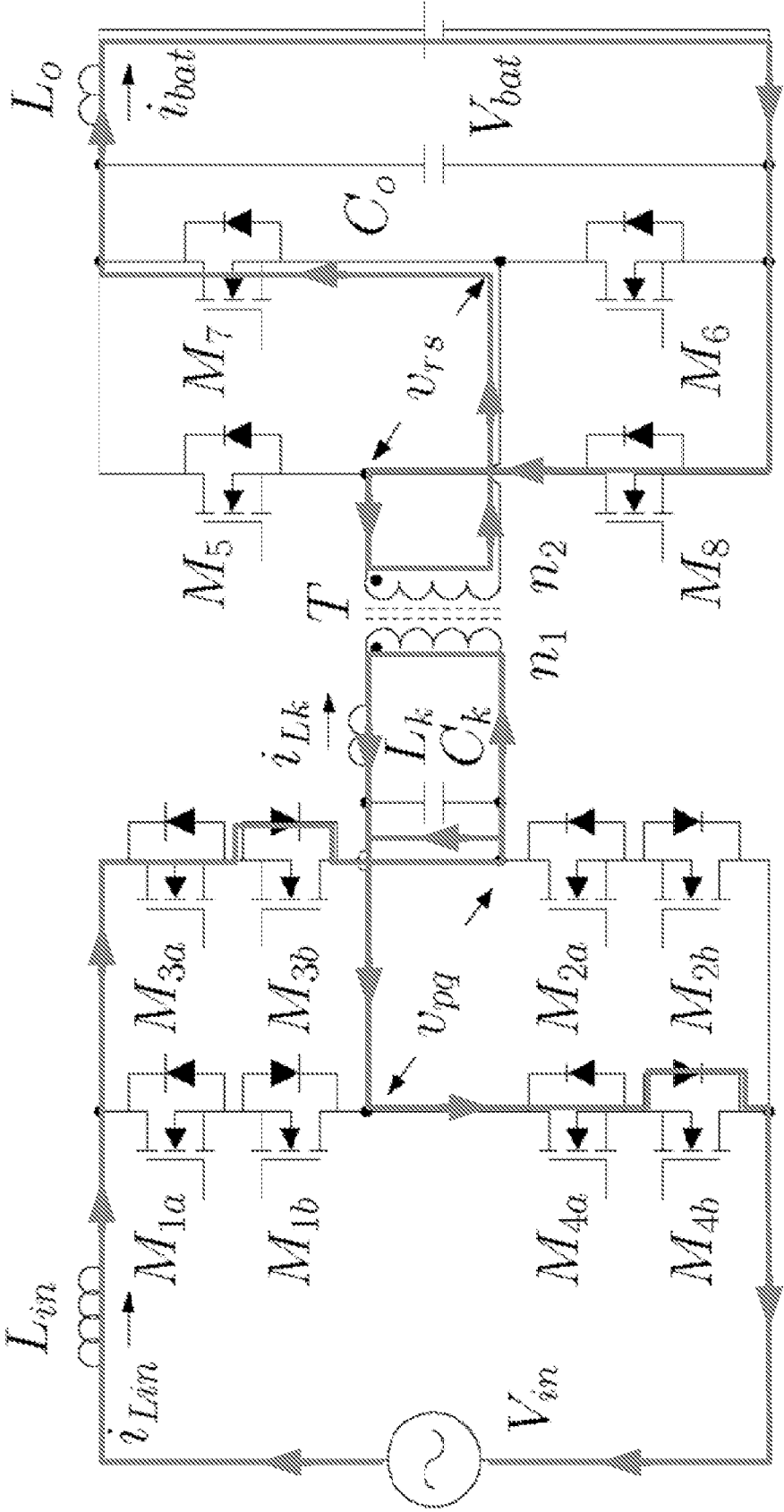


FIG. 5

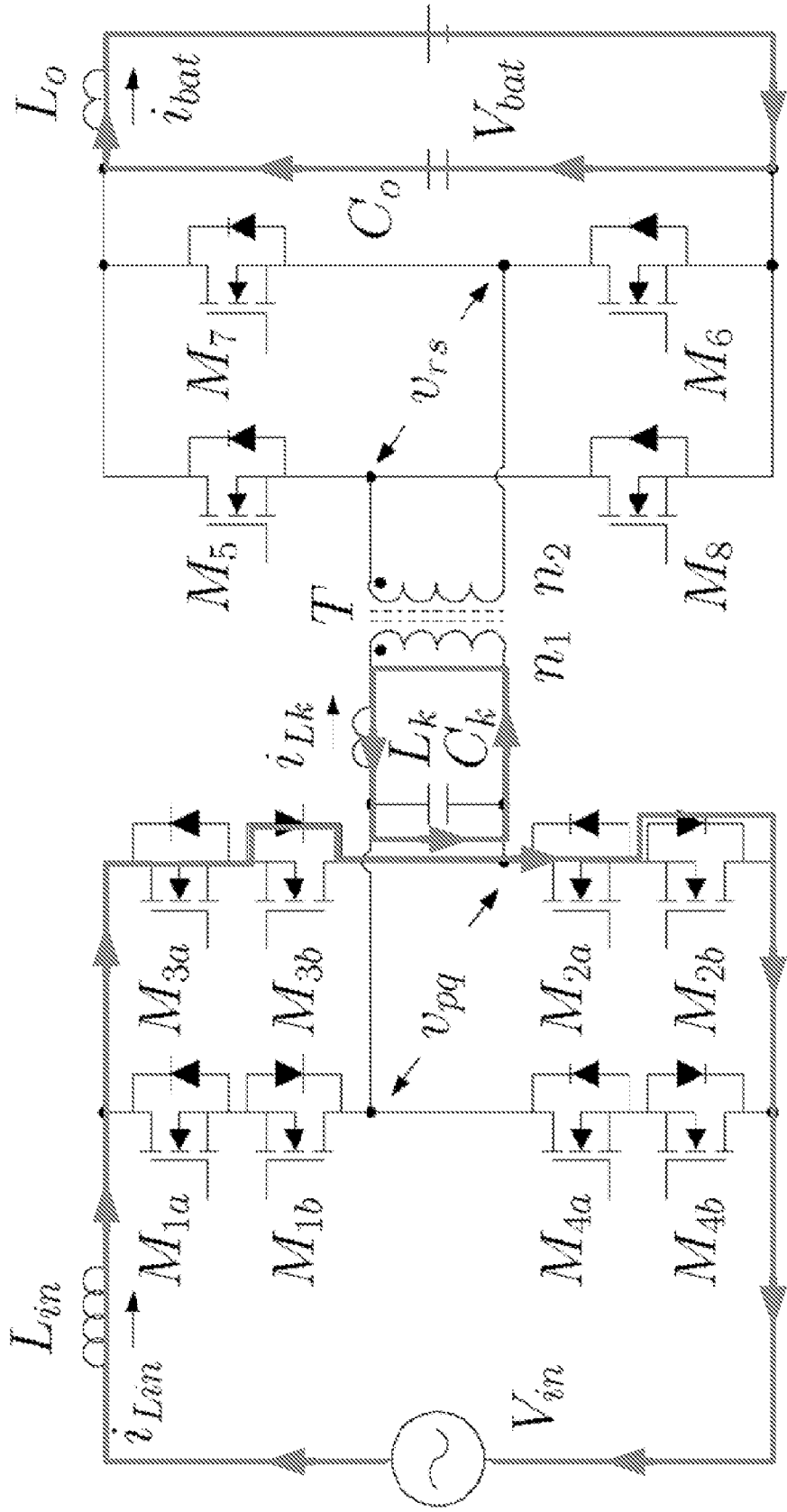


FIG. 6

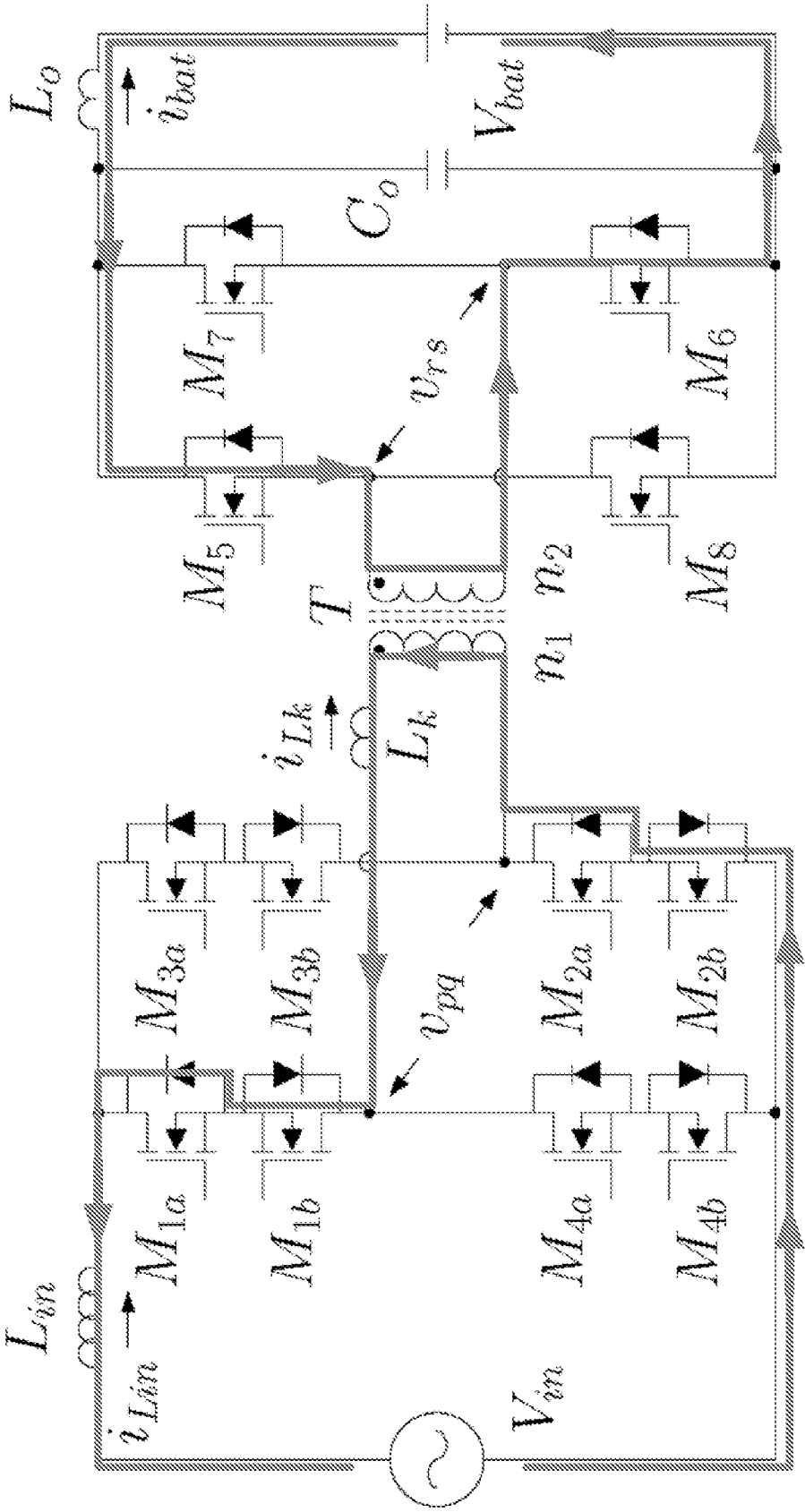


FIG. 7

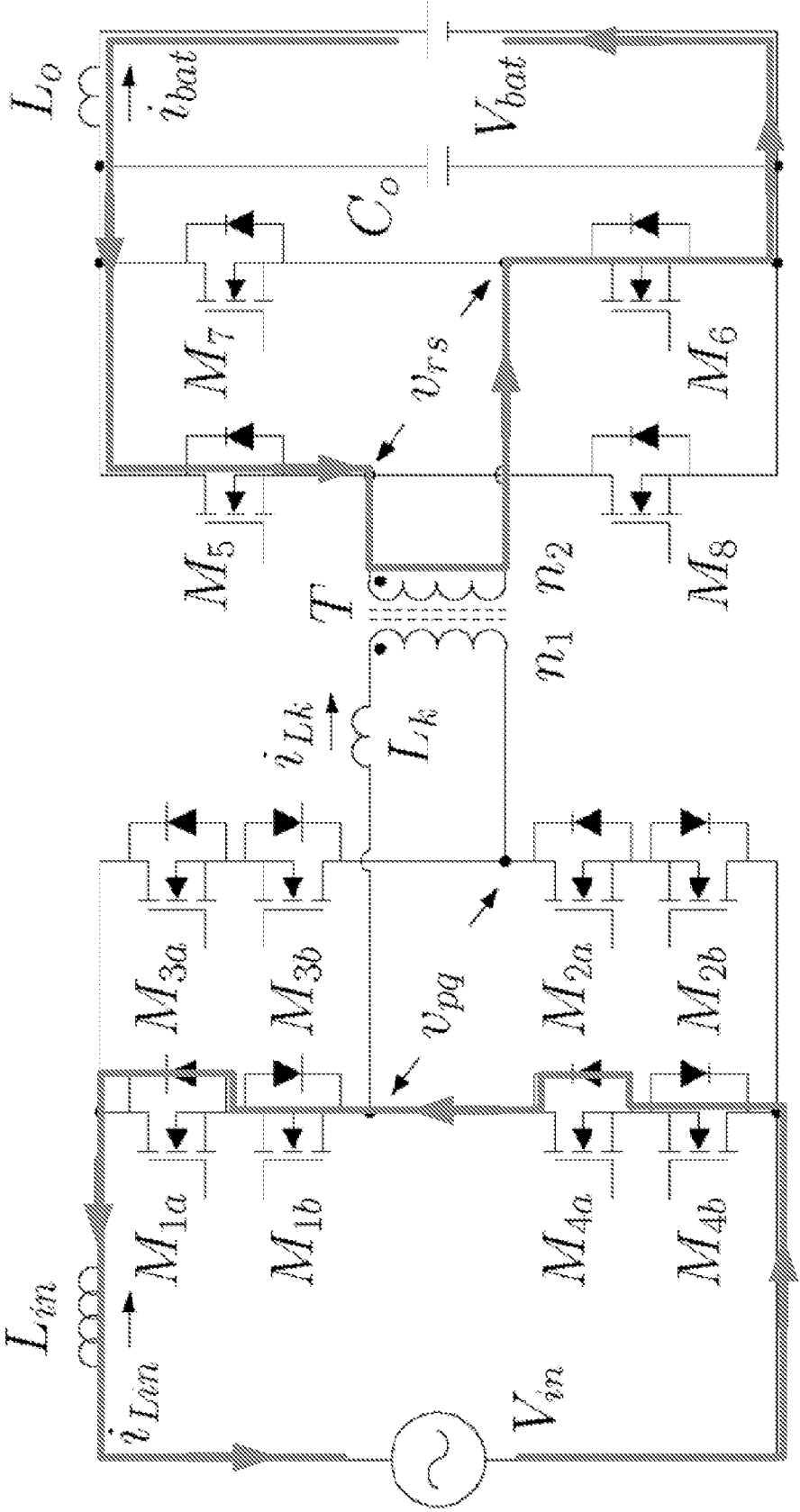


FIG. 8

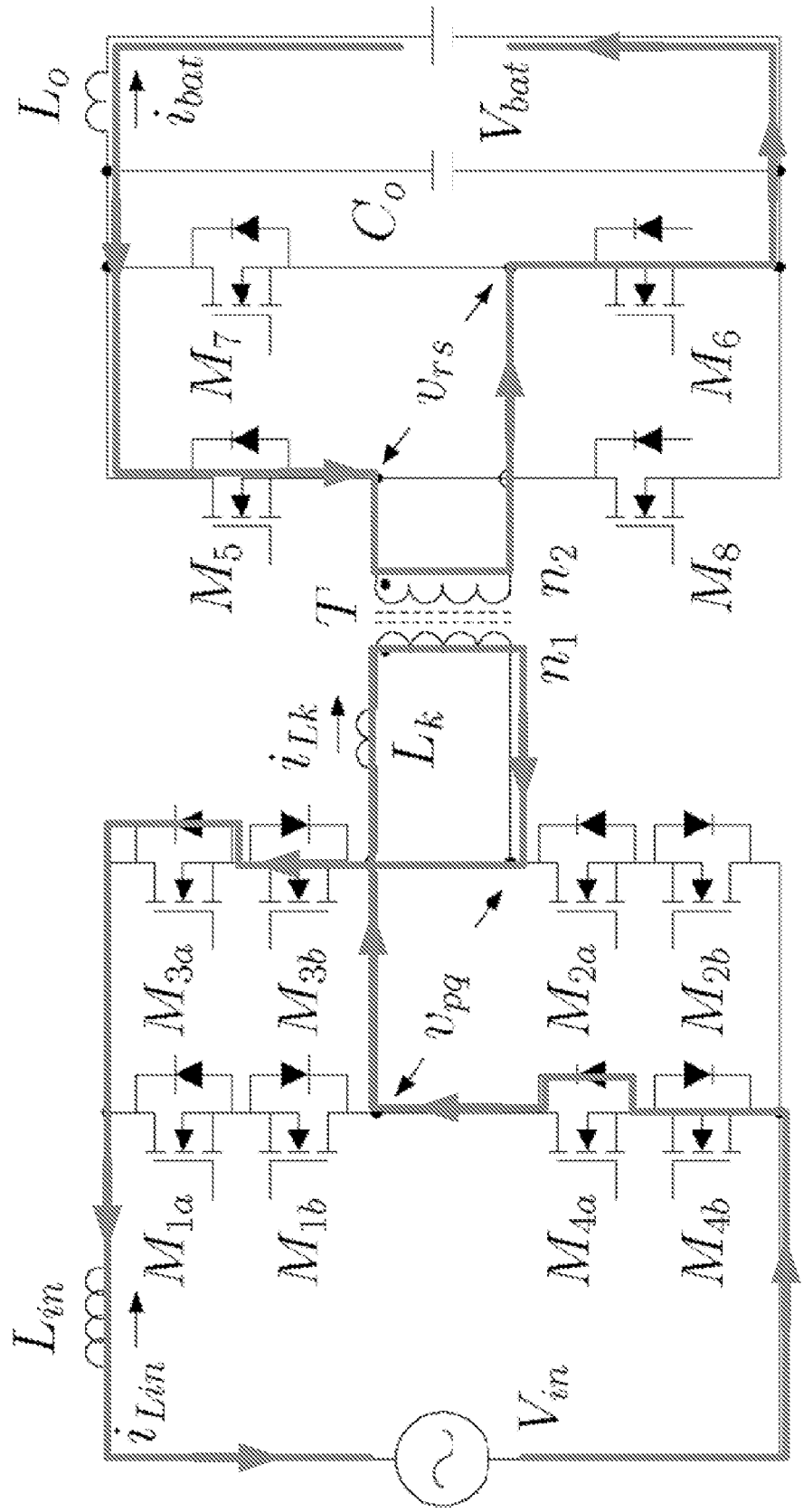
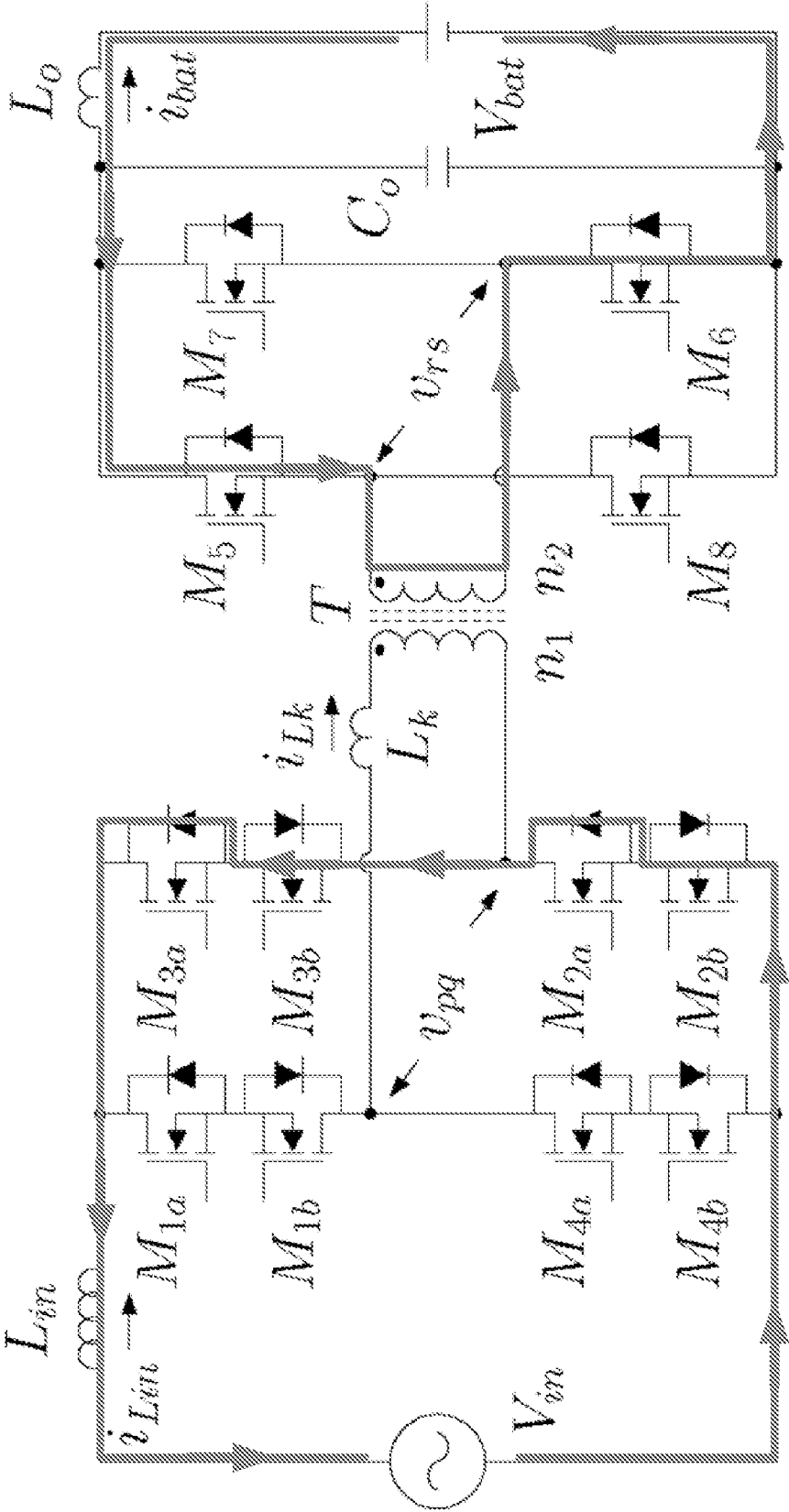


FIG. 9



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/044930

A. CLASSIFICATION OF SUBJECT MATTER INV. H02M5/297 H02M7/48 H02M7/797 H02M1/42 H02M1/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H02M		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search	Date of mailing of the international search report	
19 October 2018	08/11/2018	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Zeljko, Sandra	

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/044930

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