Downloaded from orbit.dtu.dk on: Apr 09, 2024

DTU Library

Isolated dc-dc power converter with adjustable turns ratio

Zhao, Bin; Ouyang, Ziwei; Andersen, Michael Andreas Esbern

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Zhao, B., Ouyang, Z., & Andersen, M. A. E. (2020). Isolated dc-dc power converter with adjustable turns ratio. (Patent No. *WO2020104597*).

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 May 2020 (28.05.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/104597 A1

(51) International Patent Classification:
H02M 3/335 (2006.01) *H02M 1/34* (2007.01) *H02M 1/00* (2006.01)

(21) International Application Number: PCT/EP2019/082108

(22) International Filing Date: 21 November 2019 (21.11.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
18207859.2 22 November 2018 (22.11.2018) EP

(71) Applicant: **DANMARKS TEKNISKE UNIVERSITET** [DK/DK]; Anker Engelunds Vej 101 A, 2800 Kgs. Lyngby (DK).

(72) Inventors: **ZHAO, Bin**; No. 5, Yanqi East Second Road, Huairou District, Beijing 101400 (CN). **OUYANG, Ziwei**; Cedervænget 29, st. tv., 2830 Virum (DK). **ANDERSEN, Michael Andreas Esbern**; Gurrehavevej 55, 3200 Helsinge (DK).

(74) Agent: **GUARDIAN IP CONSULTING I/S**; Diplomvej, Building 381, 2800 Kgs. Lyngby (DK).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

(54) Title: ISOLATED DC-DC POWER CONVERTER WITH ADJUSTABLE TURNS RATIO

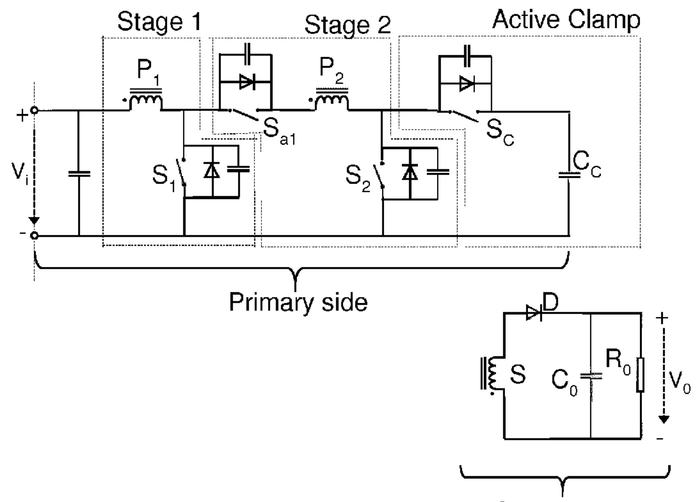

FIG. 5

(57) **Abstract:** A first aspect of the invention relates to an isolated DC-DC power converter which comprises at least one transformer which comprises a primary side winding and a secondary side winding wound on a common magnetic core. The isolated DC-DC power converter comprising a plurality of stages, each stage comprising a controllable switch and a winding inductor. The winding inductors of each two adjacent stages are connected via a controllable coupling switch so as to serially connect or disconnect these winding inductors to form the primary side winding with an adjustable number of turns. The isolated DC-DC power converter comprises a shared active clamp circuit for the controllable switches.

WO 2020/104597 A1

[Continued on next page]

GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

ISOLATED DC-DC POWER CONVERTER WITH ADJUSTABLE TURNS RATIO

A first aspect of the invention relates to an isolated DC-DC power converter which comprises at least one transformer which comprises a primary side winding and a secondary side winding wound on a common magnetic core. The isolated DC-DC power converter comprising a plurality of stages, each stage comprising a controllable switch and a winding inductor. The winding inductors of each two adjacent stages are connected via a controllable coupling switch so as to serially connect or disconnect these winding inductors to form the primary side winding with an adjustable number of turns. The isolated DC-DC power converter comprises a shared active clamp circuit for the controllable switches.

BACKGROUND OF THE INVENTION

There is an increasing demand for DC-DC power converters implemented for example as switched mode power supplies (SMPS). Advantageous DC-DC power converters are of a compact design with a high power density, use the electric input power in a highly efficient manner for generating the output power with small power losses in the conversion process, and are furthermore flexible with respect to their DC input voltage range and load current characteristics.

DC-DC power converters implemented in forward topology or flyback topology are well-known and have the further advantage of providing electric isolation between a primary side and a secondary side of the converter circuit via a transformer.

However, the transformer of the forward converter as well as of the flyback converter also has disadvantageous effects. A turns ratio between primary and secondary windings of the transformer is generally fixed. In case of a wide DC input voltage range, the fixed turns ratio of the transformer results in a large duty cycle variation of a pulse width modulation (PWM) control signal in order to maintain a target output voltage level at an output of the DC-DC power converter. A large input voltage range is a typical use scenario for a DC-DC power converter which has to operate with rectified mains voltages ranging from below 110 V to above 230 V. The large duty cycle variation is disadvantageous as a high time resolution of a PWM control signal for controlling a switch of the DC-DC converter is necessary in order to cope with the large input voltage range.

Moreover, a very small duty cycle such as 0.02 or a high duty cycle, for example 0.98, result in an undesired decrease in conversion efficiency because it induces large peak currents through the DC-DC power converter. The large peak currents lead to increased power loss and current stress in active and/or passive circuit components, such as semiconductor switches, of the DC-DC power converter.

Patent application CN 10 1171797 proposes an isolated power converter with two alternative turns ratios of an isolation transformer being available by selecting different number of windings of a primary winding of the isolation transformer and thereby adjusting the turns ratio of the isolation transformer in order to improve efficiency of the isolation transformer. The isolated power converter may operate over a wide input voltage range and for varying DC output voltages with an appropriate PWM duty cycle and a favourable high efficiency. The proposed isolated power converter includes a demagnetizing circuit using a separate demagnetizing winding N_a to discharge magnetic energy stored in the primary side winding of the isolation transformer. This particular feature disclosed in CN 10 1171797 may be helpful to avoid magnetic saturation of the magnetic core, but the demagnetizing circuit is only active when the PWM switches are in off-state and fails to achieve the benefits of a shared active clamp circuit according to the applicant’s invention.

Leakage energy which stored in a leakage inductance of the isolation transformer of a DC-DC power converter is generally dissipated in the active main or modulating switch during each off period of the switching cycle of the active main switch. Therefore degrading the energy or power efficiency of the DC-DC power converter. The use of a shared active clamp circuit on the primary side circuit of the isolated DC-DC power converter allows recycling a large portion of this leakage energy, as well as providing soft switching, or so-called ZVS or and ZCS operation, of the active main controllable switches. The present isolated DC-DC power converter allows ZVS operation of the active main switches for both low and high transformer turns ratio cases. Thereby, reducing switching losses and improving energy efficiency and power density of the converter in a manner that is particularly well-suited for high frequency operation of the applicant’s isolated DC-DC power converter. The switching frequency of the applicant’s isolated DC-DC power converter may for example be higher than 1 MHz such as higher than 3 MHz or even higher than 10 MHz.

The present isolated DC-DC power converters provides improved power efficiency under a large DC input voltage range with high energy efficiency and a relatively low component count even when using a relatively large number of individual winding segments or winding Inductors, e.g. more than 3 or 4 separate winding inductors, on the primary side winding of the isolation transformer.

SUMMARY OF THE INVENTION

The isolated DC-DC power converter according to independent claim 1 solves the technical problem in a first aspect of the invention. The dependent claims define further advantageous embodiments of the .

A DC-DC power converter according to a first aspect on the invention comprises an isolation transformer with an adjustable turns ratio. The adjustability of the turns ratio is achieved by adjusting or selecting the number of individual stages of the primary side circuit of the DD-DC power converter. Each of the stages of the power converter comprises a controllable switch and an inductor or winding segment. In order to connect two or more of the inductors, the converter comprises a further controllable coupling switch arranged in-between each pair of adjacent stages. Thus, by closing such a controllable coupling switch, two adjacent stages can be electrically coupled or interconnected such that their respective winding inductors are connected in series to commonly form the primary side winding of the isolation transformer. By connecting, starting from an input side of the DC-DC power converter, the plurality of stages successively, the primary side winding obtains an increasing number of windings. The DC-DC power converter further comprises a shared active clamped circuit for the controllable switches of the plurality of stages.

The isolated DC-DC power converter with the shared active clamp circuit and the adjustable turns ratio resulting from the further coupling switches interposed between the adjacent stages achieve improved soft switching characteristics and an advantageous recycling of leakage energy of the transformer over the switching cycle of the converter. By means of the coupling switches it is possible to electrically disconnect those stages which are unrequired to establish a desired or target turns ratio of the transformer. Due to providing a shared active clamp circuit for all switches of the plurality of stages, the beneficial soft switching characteristics are achieved at only a comparatively small number of additional components, required space and costs for the shared active clamp circuit.

This applies in particular as the driving circuit for the active clamp circuit typically is high side type driver which is particular costly to implement. Furthermore, a single additional third switch of the shared active clamp circuit increases the driving loss only disproportionally although the electric characteristics of the soft switching, particularly the recycling of leakage energy of the transformer and therefore driving losses are improved. The reduced driving loss is in particular advantageous for low power, high frequency applications. Finally, the shared active clamp circuit will improve the electric characteristics without any major decrease of the power density of the DC-DC power converter as only space for one single shared active clamp circuit is required although the overall switching behaviour of the DC-DC power converter is improved.

The DC-DC power converter according to a preferred embodiment comprises one single shared active clamp, or clamped, circuit for all the controllable switches of the plurality of stages. A single active clamp circuit for all switches optimizes the advantageous characteristics of the advantageous DC-DC power converter.

According to a preferred embodiment, the DC-DC power converter comprises a control circuit configured to control the adjustable (variable) turns ratio of the at least one isolation transformer with respective control signals for the switches of the stages and respective control signals for coupling switches interposed between the stages. Preferably, these signals are low side drive signals.

According to an advantageous embodiment of the DC-DC power converter the shared active clamp circuit comprises a separate controllable switch such as a MOSFET, IGBT switch, GaNFET switch etc. driven by a third control signal.

In an embodiment of the isolated DC-DC power converter, the control circuit is configured to drive or control the separate controllable switch of the active clamp circuit with a high side drive signal.

The controllable coupling switches of the isolated DC-DC power converter according to an embodiment are controlled such that according to a desired turns ratio, individual stages are successively connected or disconnected, by closing or opening the respective coupling switch starting from a first stage which typically is permanently connected to an input side of the isolated DC-DC power converter until the desired turns ratio is achieved. Thus, respective winding inductors of the plurality of stages can be combined so as to form a single inductor, coil or primary side winding of the isolation transformer.

Preferably, the controllable switches of the stages and the controllable coupling switches are MOSFET or GaNFET switches.

Field effect transistors (FET) on basis of GaN provide a particularly high charge carrier mobility and are most suitable for electric components and circuits in high power density applications *inter alia* due to their high breakdown voltage for high voltage applications. This is particularly useful for application in the present isolated DC-DC power converter topologies.

The isolated DC-DC power converter may for example comprise a flyback converter or forward converter.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention is described below in more detail with reference to the enclosed drawings, in which

FIG. 1 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a forward topology in a hard switching configuration to illustrate the background of the present invention,

FIG. 2 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a flyback topology in a hard switching configuration to illustrate the background of the present invention,

FIG. 3 depicts switching states and a time versus voltage chart of the flyback converter of FIG. 2 with a low transformer turns ratio,

FIG. 4 depicts switching states and a time versus voltage chart of the flyback converter of FIG. 2 with a high transformer turns ratio,

FIG. 5 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a flyback topology comprising a shared active clamp circuit in accordance with a first exemplary embodiment of the invention,

FIG. 6 shows a time chart of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a low transformer turns ratio,

FIG. 7 shows switching states corresponding to the time chart of FIG. 6 of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a low transformer turns ratio,

FIG. 8 shows a time chart of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a high transformer turns ratio,

FIG. 9 shows switching states corresponding to the time chart of FIG. 8 of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a high transformer turns ratio,

FIG. 10 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a flyback topology with N stages with a shared active clamp circuit in accordance with a second exemplary embodiment of the invention,

Fig. 11A provides simulation results for an isolated DC-DC power converter in a flyback topology according to FIG. 5 with switch S_1 acting as a main switch; and

Fig. 11B provides simulation results for an isolated DC-DC power converter in a flyback topology according to FIG. 5 with switch S_2 acting as the main switch.

In the figures, the same reference signs are used for same or corresponding elements and components. The discussion of the figures dispenses with discussing elements with the same reference signs in different figures when deemed appropriate for sake of conciseness.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

An example of a forward DC-DC power converter comprises an isolation transformer with a fixed turns ratio of the isolation transformer. When a DC input voltage V_i, which is inputted or applied to the isolated DC-DC power converter can vary over a wide voltage range a large change in a pulse width modulation (PWM) duty cycle of a control signal controlling a main switch arranged at a primary side of the isolation transformer will occur.

In a typical application, the DC-DC power converter may be adapted to accommodate mains voltages ranging from around below 110 V to above 230 V, from which the rectified DC input voltage V_i of the forward converter or flyback converter is derived.

FIG. 1 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a forward topology in a hard switching configuration. The turns ratio of the isolation transformer of the DC-DC power converter in FIG. 1 can be adjusted (varied) by appropriately controlling the controllable switches S_1, S_2 and S_{a1}. Controlling of the switches S_1, S_2 and S_{a1} can be performed according to the available DC input voltage V_i and/or a desired DC output voltage V_o. By adapting the turns ratio of isolation transformer the isolated DC-DC power converter can therefore operate always with an appropriate PWM duty cycle, i.e. avoiding extreme duty cycle ranges like below 0.05 and above 0.95. The power efficiency of the isolated DC-DC power converter of FIG. 1 is therefore high across a wide range of DC input voltages V_i. As shown in FIG. 1, the illustrated embodiment of a DC-DC power converter comprises a first stage and a second stage. Each of these stages comprises a winding inductor or winding segment P1 and P2 of the primary side winding of the isolation transformer, and a switch S_1 and S_2 respectively. The stages can be electrically connected to each other by a further, or coupling, switch S_{a1}. Closing this coupling switch S_{a1} leads to electrically connecting winding inductor P1 of the first stage and winding inductor P2 of the second stage. Thereby, the winding inductors P1 and P2 are serially connected to form the primary side winding (coil). Further stages may of course be included in the isolated DC-DC power converter as needed, wherein each of these additional stages is connected to the previously already connected stages via a further coupling switch in order to achieve a desired turns ratio of the isolation transformer. Thus, the number of windings (turns) of the primary side winding is adjusted or adapted by controlling the coupling switches S_{a1}, interposed between successive stages, to be in their open or closed states, i.e. either ON/conducting or OFF/non-conducting.

When the DC-DC power converter is operated, only the main or modulating switch S_2 of the last added stage is alternately switched, while the modulating switch S_1 is maintained in its non-conducting state or off-state.

FIG. 2 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a flyback topology. DC-DC power converters in forward topology are generally well known in the art. When comparing the forward DC-DC power converter in FIG. 1 and the flyback DC-DC power converter in FIG. 2, it is evident that both converter topologies differ merely with respect to the electric circuitry on the secondary side of the isolation transformer. The electric circuitry on the primary side of the isolation transformer of the DC-DC power converter in forward topology corresponds to the electric circuitry on the primary side of the isolation transformer of the DC-DC power converter in flyback topology.

Thus, a detailed discussion of the inventive DC-DC power converter in flyback topology with respect to FIG. 1 also applies to the DC-DC power converter in forward topology, as the inventive approach for improving DC-DC power converters in particular applies to the circuitry on the primary side of the isolation transformer.

In the schematic circuitry of FIG. 2, the isolation transformer again comprises a primary winding formed by a first winding inductor or inductance P1 of the isolation transformer and a second winding inductor or inductance P2 of the isolation transformer, wherein the primary winding has a number of windings either according to the number of windings of the first winding inductor P1 only, or the number of windings of the first winding inductor P1 plus the number of windings of the second winding inductor P2 depending of the state of the controllable coupling switch S_{A1}.

The isolation transformer further comprises a secondary winding S on its secondary side. The winding inductors P1, P2 and the secondary winding S are preferably wound around a common magnetic core of the isolation transformer. The two winding inductors P1, P2 and the secondary winding S are inversely wound on the magnetic core to implement the reverse electrical coupling of a typical flyback converter configuration.

In practice, each of the first winding inductor P1 and the second winding inductor P2 may comprise for example between 10 and 15 windings on the common magnetic core and the secondary winding S may comprise 2 windings on the common magnetic core.

The controllable switches S_1, S_2, S_{a1} of the primary side circuit of the converter are arranged on the primary side of the isolation transformer and each of the controllable switches S_1, S_2, S_{a1} is preferably a semiconductor switch. The controllable switches S_1, S_2, S_{a1} can be semiconductor devices in MOSFET or GaN-FET technology. Due to a high mobility of charge carriers, GaN-FETs are particularly useful for power electric applications with a high power density and therefore particularly advantageous in combination with the present DC-DC power converter topology, when compared, for example with Si based MOSFETs.

C_i is an input capacitor connected across the input terminals of the converter for receipt of the DC input voltage V_i on the primary side of the isolated DC-DC power converter.

D is a diode rectifier circuit element on the secondary side of the isolation transformer. The diode D can be replaced by an active switch such as a MOSFET or GaNFET for a synchronous active type of rectifier in a specific embodiment of the DC-DC power converter.

C_o is an output capacitor arranged on the secondary side of the isolation transformer of the DC-DC power converter in order to suppress ripple voltages and smoothen the DC output voltage V_o provided between output terminals of the DC-DC power converter. A schematically illustrated load circuit R_n is coupled to the DC output voltage V_o of the DC-DC power converter.

It is evident to the skilled person that while the illustrated embodiment in FIG. 2 as well as the corresponding DC-DC power converter in forward topology in FIG. 1 merely shows two stages in the primary side circuitry, with separate inductors P1 and P2 respectively for the sake of simplicity.

Other embodiments of the DC-DC power converter may comprise three, four or even more, in general terms N serially connectable individual stages with respective winding inductors P1, P2, P3, …, PN of the primary side winding of the isolation transformer and corresponding semiconductor switches S_1, S_{a1}, S_2, …, $S_{a(N-1)}$, S_N. These additional input stages up to input stage N are arranged in series with each other beginning with the first stage being permanently connected with the input side of the DC-DC power converter followed by the second stage shown on the primary side of the isolation transformer in FIGS. 1 and 2.

FIG. 3 depicts switching states and a time chart of control signals used for controlling the open/closed state of the controllable switches of the flyback converter of FIG. 2 operating with a low transformer turns ratio n being selected. The exemplary embodiment is a flyback DC-DC power converter with a first stage and a second stage. The flyback DC-DC converter operates in a continuous-conduction-mode (CCM). It is to be noted, that all control signals that are described in the following for explaining the operation and function of the DC-DC power converter are generated by a microcontroller and output individually to the respective controllable switch. Thus, each controllable switch mentioned herein is controlled by an output control signal received from the microcontroller.

A low transformer turns ratio n, such less than 8 or 5.5, may apply in a phone adaptor application when the DC input voltage V_i is relatively low, for example. Only the first stage on the primary side circuit operates. Thus, controllable switch S_1 of the first stage works as a main modulating switch for example as a PWM switch. Both, the further controllable switch S_{a1} and the switch S_2 of the second stage are in a non-conducting state (off state) during the entire switching period of the main switch, thus, all the time. Hence, merely the first stage and the windings of the first winding inductor P1 of the isolation transformer are active when the switch S_1 of the first stage is alternately switched between On and Off states.

During a first time interval lasting from t = 0 to t = DT with D being the pulse width modulation duty cycle and T being the switching period of the controllable switch S_1, the controllable switch S_1 is in a conducting state. The diode D on the secondary side of the isolation transformer is reverse biased. The input voltage V_i crosses an isolation barrier implemented by the isolation transformer from the first inductor P1 to the secondary winding S.

During a second time interval lasting from t = DT to t = T, the switch S_1 of the first stage is in non-conducting state (off-state). The diode D on the secondary side of the isolation transformer is forward biased, while the controllable switch S_1 is non-conducting.

A voltage transfer function of the DC-DC power converter can be derived by evaluating the voltage balance over the inductive component

$$V_i \times DT = nV_o \times (1 - D)T; \qquad (1)$$

The voltage transfer function is

$$\frac{V_o}{V_i} = \frac{D}{n(1-D)}\ ; \qquad (2)$$

with the DC input voltage V_i, the DC output voltage V_o, the PWM duty cycle D, the isolation transformer turns ratio n.

FIG. 4 depicts switching states of the flyback converter of FIG. 2 with a high transformer turns ratio n, in a time chart. The exemplary embodiment is a flyback DC-DC power converter with a first stage and a second stage. The flyback DC-DC

converter operates in a continuous-conduction-mode (CCM). A high transformer turns ratio n may apply in a phone adaptor application when the DC input voltage V_i is high. For a relatively high input voltage V_i, the first stage 1 and the second stage 2 on the primary side circuit of the converter are connected in series which specifically means that the winding inductors P1 and P2 of the first stage and the second stage, respectively, are connected in series. In order to connect the winding inductors P1 and P2 of the first stage 1 and the second stage 2 in series, the controllable coupling switch S_{a1} is switched to its conducting state by the controller over the entire switching period T, thus, all the time.
The controllable switch S_2 of the second stage now acts as a main PWM switch and the controllable switch S_1 of the first stage is switched to a non-conducting state by the controller during the entire switching period of the main switch S_2, thus, all the time. Hence, when both the first stage 1 and the second stage 2 are active their winding inductors P1 and P2 commonly form the primary side winding of the isolation transformer. A power transfer from the primary side of the isolation transformer to the secondary side of the isolation transformer is achieved via first and second winding inductors P1, P2, which are now connected in series to the secondary winding S, thereby establishing a turns ratio different from the one of FIG. 2, where the turns ratio is defined only by the number of windings of the first winding inductor P1 and the number of turns of the inductor on the secondary side. Obviously, the number of turns of the winding on the secondary side is constant.

During a first time interval lasting from t = 0 to t = DT the controllable switch S_2 is in a conducting state. D is the pulse width modulation duty cycle and T is the switching period of the controllable switch S_2. The diode D on the secondary side of the isolation transformer is reverse biased. It is assumed that first inductor P1 and second inductorP2 comprise both n turns and the secondary winding is assumed to include one turn. Then, only half of the input voltage V_i crosses the isolation barrier implemented by the isolation transformer from the first inductor P1 and the second inductor P2 on the one hand to the secondary winding S on the other hand.

During a second time interval ranging from t = DT to t = T, the main switch S_2 is in non-conducting state. The diode D on the secondary side of the isolation transformer is forward biased, while the controllable switch S_2 is non-conducting.

A voltage transfer function of the DC-DC power converter can be derived by evaluating the voltage balance over the inductive component

$$0.5V_i \times DT = nV_o \times (1 - D)T; \tag{3}$$

The voltage transfer function is

$$\frac{V_o}{V_i} = \frac{D}{2n(1-D)}; \tag{4}$$

with the DC input voltage V_i, the DC output voltage V_o, the PWM duty cycle D and the isolation transformer turns ratio n.

Fig. 5 is a simplified electrical circuit diagram of an isolated DC-DC power converter in a flyback topology with a shared active clamp circuit 2 in accordance with a first exemplary embodiment of the of the isolated DC-DC power converter.

The first and second stages of the DC-DC power converter depicted in FIGS. 3 and 4 show hard switching characteristics, in particular due to the leakage inductance of the winding inductors P1 and P2 in the isolation transformer.

According to the present embodiment, the first and second stage on the primary side circuit of the isolated DC-DC power converter commonly comprise one shared active clamp circuit 2. The shared active clamp circuit 2 is arranged in series with the first stage with its first winding inductor P1 and the second stage with its second winding inductor P2 each as shown in FIG. 5.

The shared active clamp circuit 2 of the first embodiment comprises a clamp capacitor C_C in series with a controllable clamp switch S_C. This controllable switch S_C of the shared active clamp circuit 2 is shown with its parasitic switch capacitor and parasitic pn diode.

FIG. 6 shows a time domain plot or chart of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit 2 of FIG. 5 in an application with a low transformer turns ratio. A low transformer turns ratio n may apply in a phone adaptor application when the DC input voltage V_i is low.

FIG. 7 shows the switching states corresponding to the time chart of FIG. 6 of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a low transformer turns ratio. For adjusting the transformer's turns ratio n to a low turns ratio value, the first stage only works together with the shared active clamp circuit 2. Therefore, the controllable switch S_1 of the first stage functions as the main PWM switch. The controllable switch S_2 is constantly in a non-conducting state (off state). The controllable coupling switch S_{a1} connecting the first inductor P1 and the second inductor P2, and controllable switch S_C of the shared active clamp circuit have a common control signal scheme to function as the active clamp switches. The low turns ratio may be 5.5 and for example selected by the controller, e.g. programmable microcontroller or microprocessor, of the isolated DC-DC power converter in response to the DC input voltage V_i lies between 60 V and 150 V, while the high turns ratio may be larger than 10 or 11 and selected by the microcontroller in response to the DC input voltage V_i exceeds 150 V.

During a first time interval lasting from t = 0 to t = DT, the controllable switch S_1 is in a conducting state. The other controllable switches S_{a1}, S_2, and S_C are all switched to their respective non-conducting states. The diode D on the secondary side of the isolation transformer is reverse biased. The DC input voltage V_i is applied solely across the first winding inductor P1 during the first time interval.

The second time interval lasting from t = DT to t = DT+d1 is a first dead zone (first dead time interval) in which all controllable switches S_{a1}, S_2, S_C including switch S_1 acting as the main or modulating switch of the flyback converter are in non-conducting states. During the second time interval, the output capacitor C_o arranged on the secondary side of the isolation transformer begins to accumulate charge and accordingly the output voltage across the capacitor C_o begins to rise.

In the third time interval from t = (DT+d1) to t = (DT+d2), both the controllable coupling switch S_{a1} and controllable clamp switch S_C are placed in their respective conducting states. Now energy stored in a leakage inductance of the isolation transformer begins to discharge to the clamp capacitor C_c. The diode D is now forward biased. The third time interval ends when the current through the first and second winding inductors P1 and P2 into the clamp capacitor C_C reaches zero.

During the fourth time interval from t = (DT+d2) to t = (DT+d3), the controllable coupling switch S_{a1} and controllable clamp switch S_C are still in a conducting state. The leakage inductance energy has been fully released or discharged during the preceding third time interval. Now, the clamp capacitor C_c begins to discharge and the current through the first and second primary side winding inductors P1, P2 is reversed. The rectification diode D on the secondary side of the isolation transformer is forward biased.

The fifth time interval ranges from t = (DT+d3) to t = T. The fifth time interval represents a second dead zone (second dead time interval), in which all controllable switches S_1, S_{a1}, S_2 and S_C are switched into their respective non-conducting states. The energy stored in the output capacitor of S_1 releases to maintain the current still flowing in the reverse direction. Now, the output voltage V_o starts to drop while D is still forward biased. When the voltage drops to zero, the controllable switch S_1 of the first stage is switched back into its conducting state. The next switching cycle of the present flyback converter starts accordingly with a smooth zero voltage switching (ZVS) in a continuous conduction mode CCM of operation.

The voltage transfer function of the first embodiment of the DC-DC power converter with soft switching due to the shared active clamped stage corresponds to the voltage transfer function as discussed with respect to FIG. 5 for hard switching and is cited in equation (2). The first and second dead time intervals result in achieving an advantageous ZVS behavior for the main switch of the DC-DC power converter.

FIG. 8 shows a time chart of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit of FIG. 5 with a high transformer turns ratio.

FIG. 9 shows the respective switching states corresponding to the time chart of FIG. 8 of the isolated DC-DC power converter in a flyback topology with the shared active clamp circuit 2 of FIG. 5 with a high transformer turns ratio.

The embodiment is a flyback DC-DC power converter with a first stage and a second stage and a shared active clamp circuit 2 arranged in series to the first stage and the second stage. The flyback DC-DC converter operates in a continuous-conduction-mode (CCM). A high transformer turns ratio n may apply in a phone adaptor application when the DC input voltage V_i is high.

In the embodiment of FIGs 8 and 9, the further controllable switch S_{a1} is set to a conducting state during the entire switching period or cycle of the main switch of the flyback converter. Thus, the winding inductor P1 of the first stage and the winding inductor P2 of the second stage are electrically connected to each other through the coupling switch such that they commonly form the primary side winding with a large number of windings when compared to the number of windings of the first inductor P1 only. Consequently, also the turns ratio of the transformer of the inventive power converter is adapted. Now, the controllable modulating switch S_2 of the second stage, which in the illustrated embodiment is of course the last added stage, functions as the main switch for controlling the modulation of the DC input voltage for example using PWM modulation. The controllable switch S_1 is in a non-conducting state during the switching cycle so that the combination of the first winding inductor P1 and the second winding inductor P2 commonly can act as one single primary side winding of the isolation transformer. The controllable clamp switch S_C functions as active clamp switch of the shared active clamp circuit 2.

During a first time interval ranging from t = 0 to t = DT, the controllable modulating switch S_2 of the second stage and the coupling switch S_{a1} connecting the first stage and the second stage are in placed in respective conducting states. During the first time interval, the other controllable switches S_1 and S_C are in a non-conducting state. The diode D is reverse biased. Across the first winding inductor P1 one-half of the DC input voltage applies when the first winding inductor P1 equals the second inductor P2 with respect to the number of turns or windings.

The second time interval lasts from t = DT to t = DT+d1 and is a first dead zone or first dead time interval in which the controllable switches S_1, S_2 and S_C are in respective non-conducting states. During the second time interval, the output capacitor C_o arranged on the secondary side circuit of the converter, and of the isolation transformer, begins charging. Therefore, the voltage across the capacitor C_o begins to increase or rise.

In the third time interval from t = (DT+d1) to t = (DT+d2), controllable coupling switch S_{a1} and the clamp switch S_C are in a conducting state. Now, energy stored in a leakage inductance of the isolation transformer begins to discharge into the clamp capacitor C_c. The diode D is now forward biased. The third time interval ends when the current through the first and second inductors P1 and P2 into the clamp capacitor C_C reaches zero.

During the fourth time interval from t = (DT+d2) to t = (DT+d3), the controllable coupling switch S_{a1} and the clamp switch S_C are still in respective conducting states. The leakage inductance energy has been fully discharged or released in the preceding third time interval. Now, the clamp capacitor C_c begins to discharge and the current through the first and second inductors P1, P2 is reversed. The diode D on the secondary side of the isolation transformer is still forward biased.

The fifth time interval lasts from t = (DT+d3) to t = T. The fifth time interval is the second dead zone, in which the controllable switches S_1, S_2 and S_C are switched to their respective non-conducting states. The energy stored in the output capacitor of S_1 releases or discharges to maintain the current still in the reversed direction. The voltage V_O starts to drop while diode D on the secondary side of the isolation transformer is still forward biased. When the voltage reaches a value of zero, the controllable switch S_2 is switched to the conducting state. The next switching cycle of the flyback converter starts accordingly with a smooth zero voltage switching (ZVS) in a continuous conduction mode CCM.

The preceding sections discuss an embodiment of the invention with reference to a flyback converter in CCM mode of operation. The DC-DC power converter with further switches connecting and disconnecting inductors of additional stages and with a shared active clamp circuit invention is also applicable in a discontinuous mode of operation (DCM).

The variable turns ratio of the isolation transformer due to multiple stages being connected on the primary side using interposed further switches of the isolation transformer in combination with a shared active clamp circuit are key features of the innovative flyback and forward DC-DC power converters.

FIG. 10 is a simplified electrical circuit diagram of an isolated DC-DC power converter 5 in a flyback topology or forward topology with N stages with a shared active clamp circuit 2 in accordance with a second exemplary embodiment of the invention.

The second embodiment may correspond to the isolated DC-DC power converter in a flyback topology with N stages with a shared active clamp circuit 2 of the first embodiment. The skilled person will appreciate that merely the position of the shared active clamp circuit 2 in the primary side circuit is changed in the circuitry according to FIG. 10. The advantageous characteristics and benefits of the isolated DC-DC power converter according to FIG. 10 correspond to those characteristics and benefits of the isolated DC-DC power converter according to FIG. 5 and reference to the above discussion of FIG. 5 is considered sufficient for sake of conciseness. The only difference that occurs is that the active clamp circuit 2 is connected to the last available stage of the primary side circuit and all intermediate stages between the first stage on the primary side or input side and the last stage need to be connected while switch S_C is closed.

FIG. 11A provides simulation results for an isolated DC-DC power converter in a flyback topology according to FIG. 5 with the controllable switch S_1 of the first stage acting as a main or modulating switch of the converter It is evident from the plot in FIG. 11A that for the DC-DC power converter with the shared active clamp circuit 2, before the controllable switch S_1 of the first stage is closed, a drain-source voltage $V_{ds1}(t)$ across switch S_1 has reached zero. As a result, when the controllable switch S_1 is switched to a conducting state, a zero-voltage-switching (ZWS) of the controllable switch S_1 is achieved.

Fig. 11B provides simulation results for an isolated DC-DC power converter in a flyback topology according to FIG. 5 with the controllable switch S_2 acting as the main or modulating switch. Similar to FIG. 11A, FIG. 11B demonstrates that with the shared active clamp circuit 2, before the switch S_2 is closed, a voltage $V_{ds2}(t)$ over the switch S_2 has decreased to a value of zero. As a result, when the switch S_2 is closed (switched into a conducting state), zero-voltage-switching of the controllable switch S_2 of the second stage is achieved.

The voltage versus time plots in FIGS. 11A and 11B depict simulations, which validate the performance and properties for a DC-DC power converter with the shared active clamp circuit 2. The DC-DC power converter with the shared active clamp circuit 2 enables high power efficiency and high power density. This results from a decreased volume of the passive components by increasing the switching frequency.

The inventive DC-DC power converters achieve high efficiency and high power density by reducing the switching losses and recycling the leakage energy of the primary side winding inductors or winding segments by using the shared active clamp circuit.

CLAIMS

1. An isolated DC-DC power converter, comprising

at least one transformer comprising a primary side winding and a secondary side winding wound on a common magnetic core;

a plurality of stages, each stage comprising a controllable switch (S_1, S_2,…, S_N) and an inductor (P1, P2,…, PN), and

wherein the inductors (P1, P2,…, PN) of each two adjacent stages are connected via a further controllable switch (S_{1a}, S_{2a}), respectively, so as to serially connect or disconnect these inductors (P1, P2,…, PN) to provide the primary side winding with an adjustable number of turns, wherein

the isolated DC-DC power converter comprises a shared active clamp circuit (2) for the controllable switches (S_1, S_2…, S_N).

2. The isolated DC-DC power converter according to claim 1, wherein

the DC-DC power converter comprises a single shared active clamp circuit (2) for the controllable switches (S_1, S_2,…, S_N) of the plurality of stages of the DC-DC power converter.

3. The isolated DC-DC power converter according to claim 1 or 2, wherein

the DC-DC power converter comprises a control circuit configured to control the variable turns ratio of the at least one transformer with control signals for the controllable switches (S_1, S_2,…, S_N) of the plurality of stages and the controllable coupling switches (S_{1a}, S_{2a}) interposed between the plurality of stages.

4. The isolated DC-DC power converter according to claim 3, wherein the control signals for the controllable switches (S_1, S_2,…, S_N) are low side drive signals and the control signals for the controllable coupling switches (S_{1a}, S_{2a}) are high side drive signals.

5. The isolated DC-DC power converter according to any of claims 1 to 4, wherein

the shared active clamp circuit (2) comprises a controllable clamp switch (S_c).

6. The isolated DC-DC power converter according to claim 5, wherein

the control circuit is configured to apply a high side drive signal to a control terminal, such as a gate terminal, of the controllable clamp switch (S_c).

7. The isolated DC-DC power converter according to claim 6, wherein

the control circuit is configured to successively connect stages to a first stage of the plurality of stages which is permanently connected to an input side of the DC-DC power converter, thereby establishing the desired amount of primary side windings for adjusting the turns ratio of the transformer.

8. The isolated DC-DC power converter according to any one of claims 1 to 7, wherein

the controllable switches (S_1, S_2,..., S_N) and the at least one controllable coupling switch (S_{1a}, S_{2a},) for connecting the stages are MOSFET or GaNFET switches.

9. The isolated DC-DC power converter according to any of claims 1 to 8, comprising a flyback converter or forward converter.

10. The isolated DC-DC power converter according to any of the preceding claims, comprising between two and six individual stages connected to a primary side circuit of the DC-DC power converter.

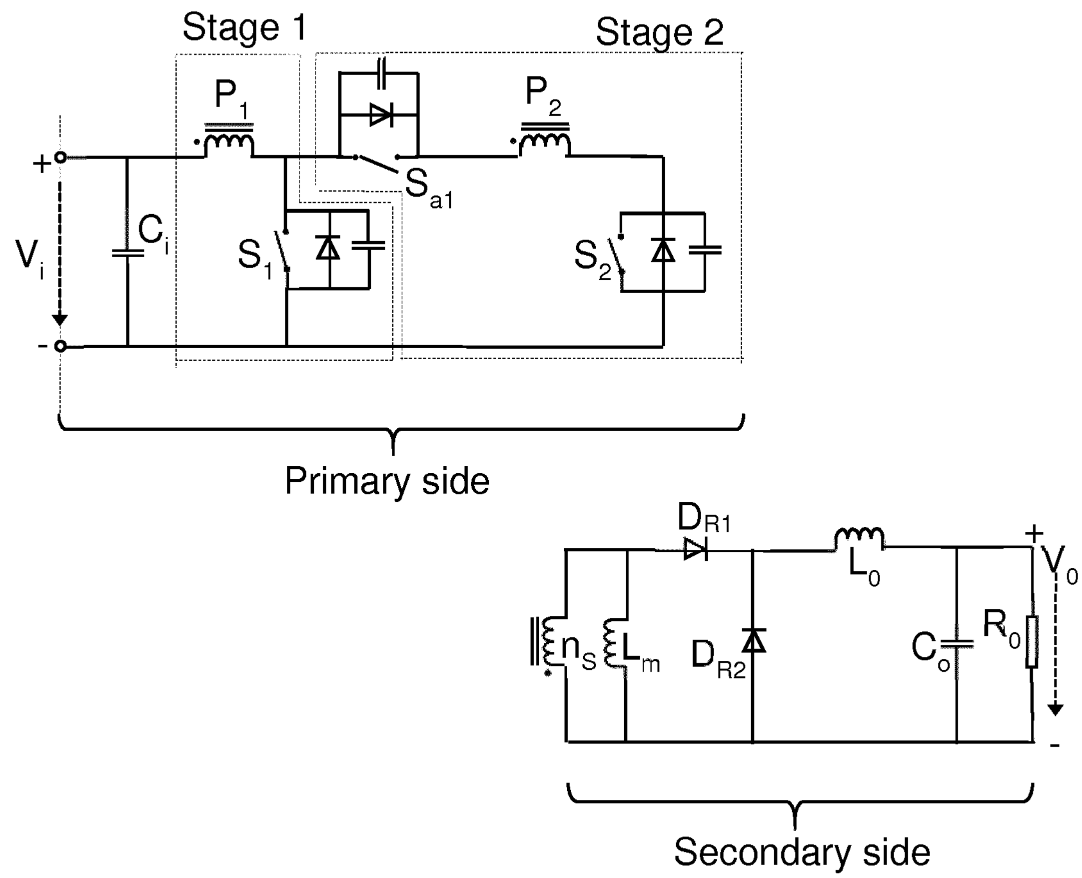
Stage 1
Stage 2
P1
P2
Sa1
+
Vi
-
Ci
S1
S2
Primary side
DR1
L0
V0
nS
Lm
DR2
Co
R0
Secondary side

FIG. 1

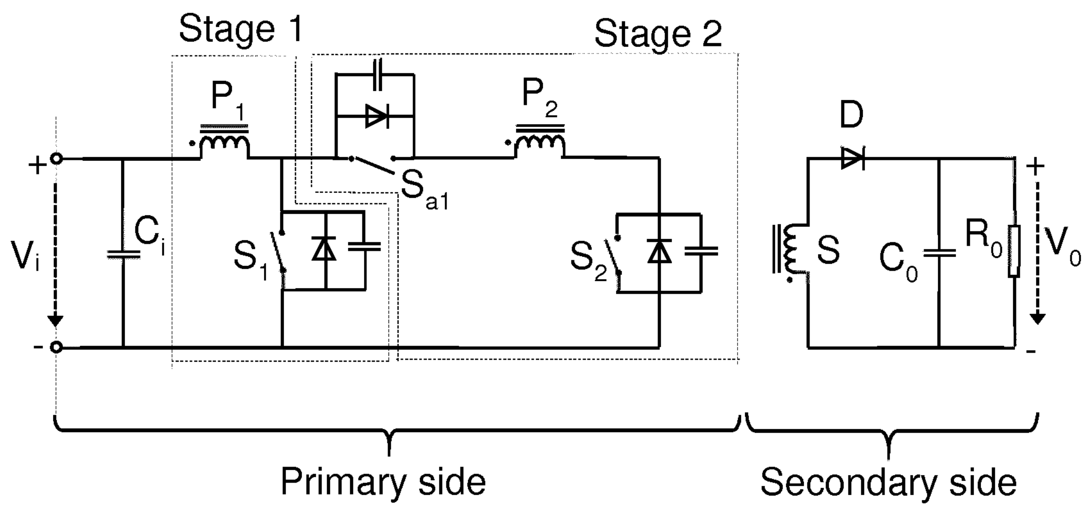
Stage 1
Stage 2
P1
P2
Sa1
+
Vi
-
Ci
S1
S2
D
S
C0
R0
V0
Primary side
Secondary side

FIG. 2

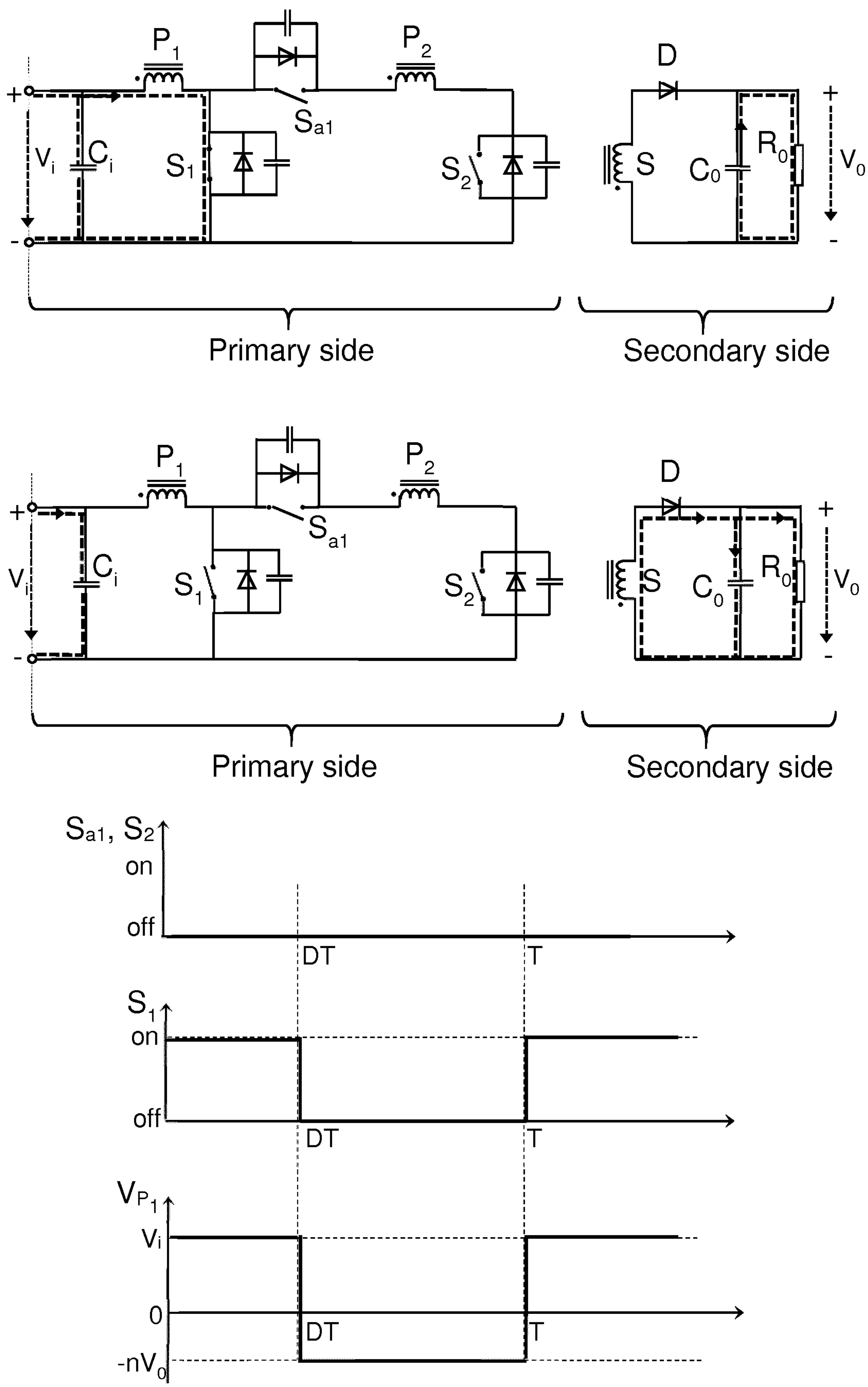
P1
Sa1
P2
D
Vi
Ci
S1
S2
S
C0
R0
V0
Primary side
Secondary side
P1
Sa1
P2
D
Vi
Ci
S1
S2
S
C0
R0
V0
Primary side
Secondary side
Sa1, S2
on
off
DT
T
S1
on
off
DT
T
VP1
Vi
0
DT
T
-nV0

FIG. 3

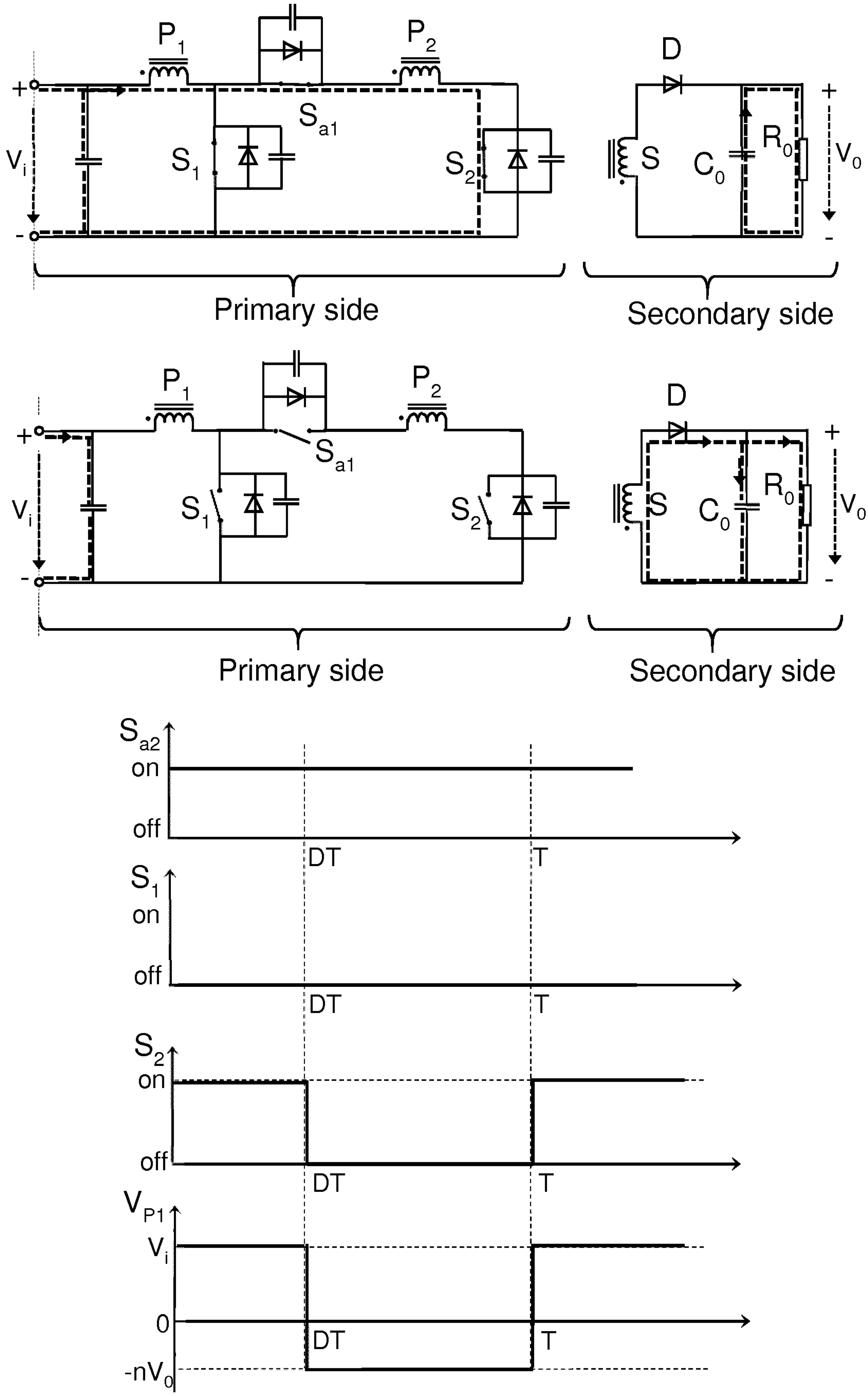
P1
P2
Sa1
S1
S2
Vi
+
-
D
S
C0
R0
V0
Primary side
Secondary side
P1
P2
Sa1
S1
S2
Vi
D
S
C0
R0
V0
Primary side
Secondary side
Sa2
on
off
DT
T
S1
on
off
DT
T
S2
on
off
DT
T
VP1
Vi
0
-nV0
DT
T

FIG. 4

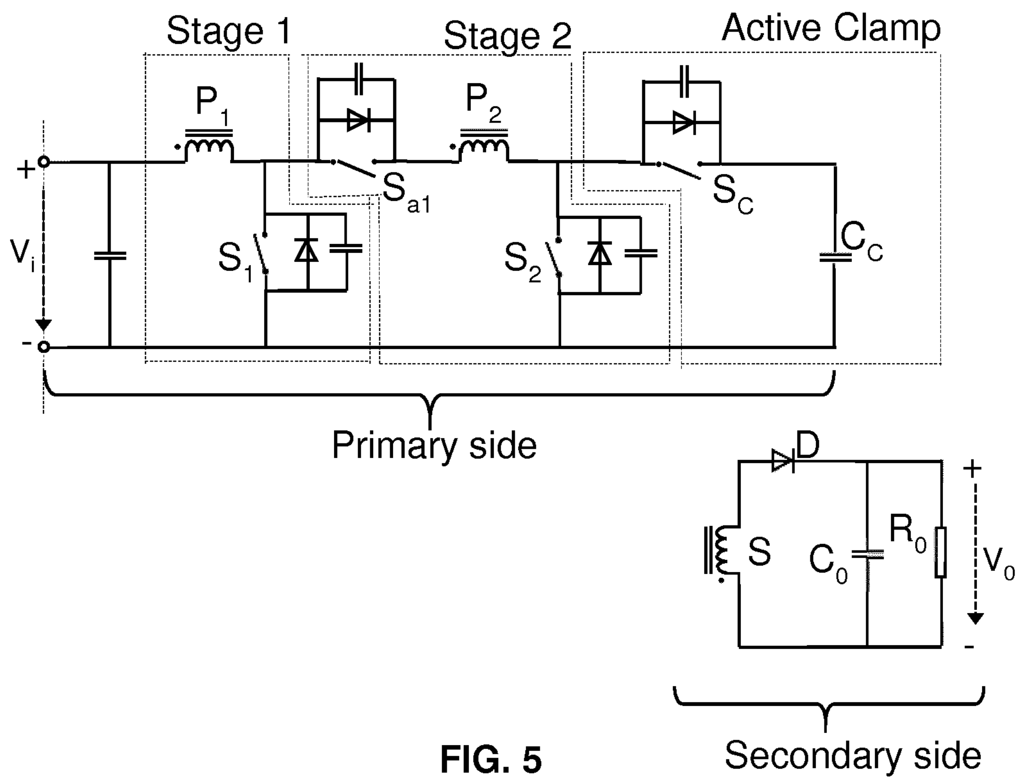
Stage 1
Stage 2
Active Clamp
P1
P2
Sa1
SC
S1
S2
CC
Vi
+
-
Primary side
D
S
C0
R0
V0
Secondary side

FIG. 5

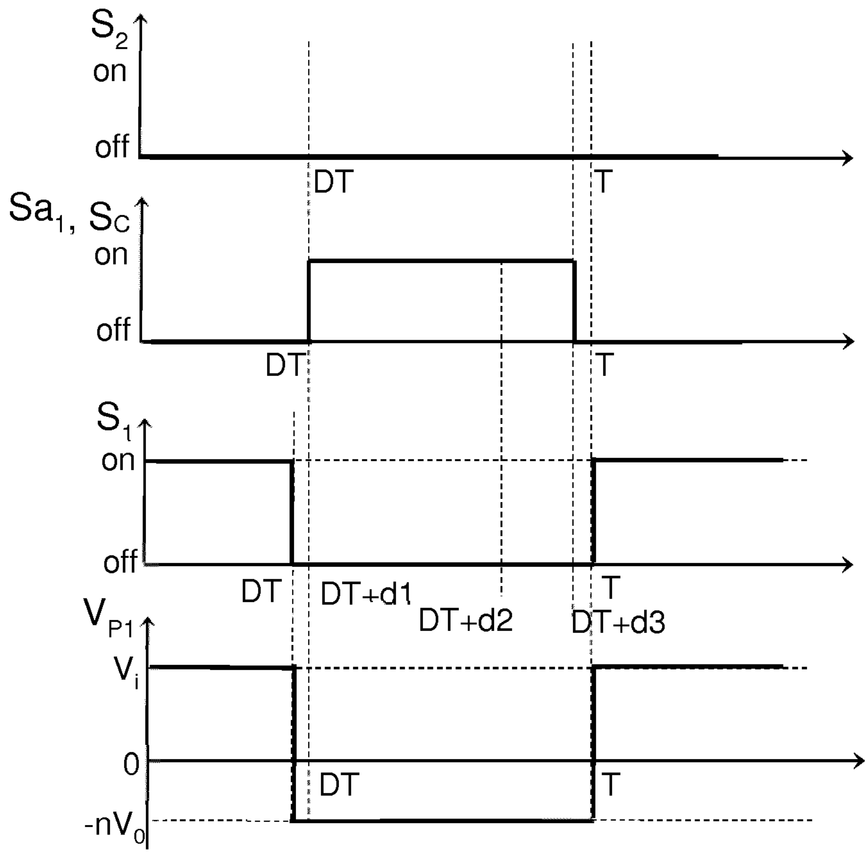
S2
on
off
DT
T
Sa1, SC
on
off
S1
on
off
DT+d1
DT+d2
DT+d3
VP1
Vi
0
-nV0

FIG. 6

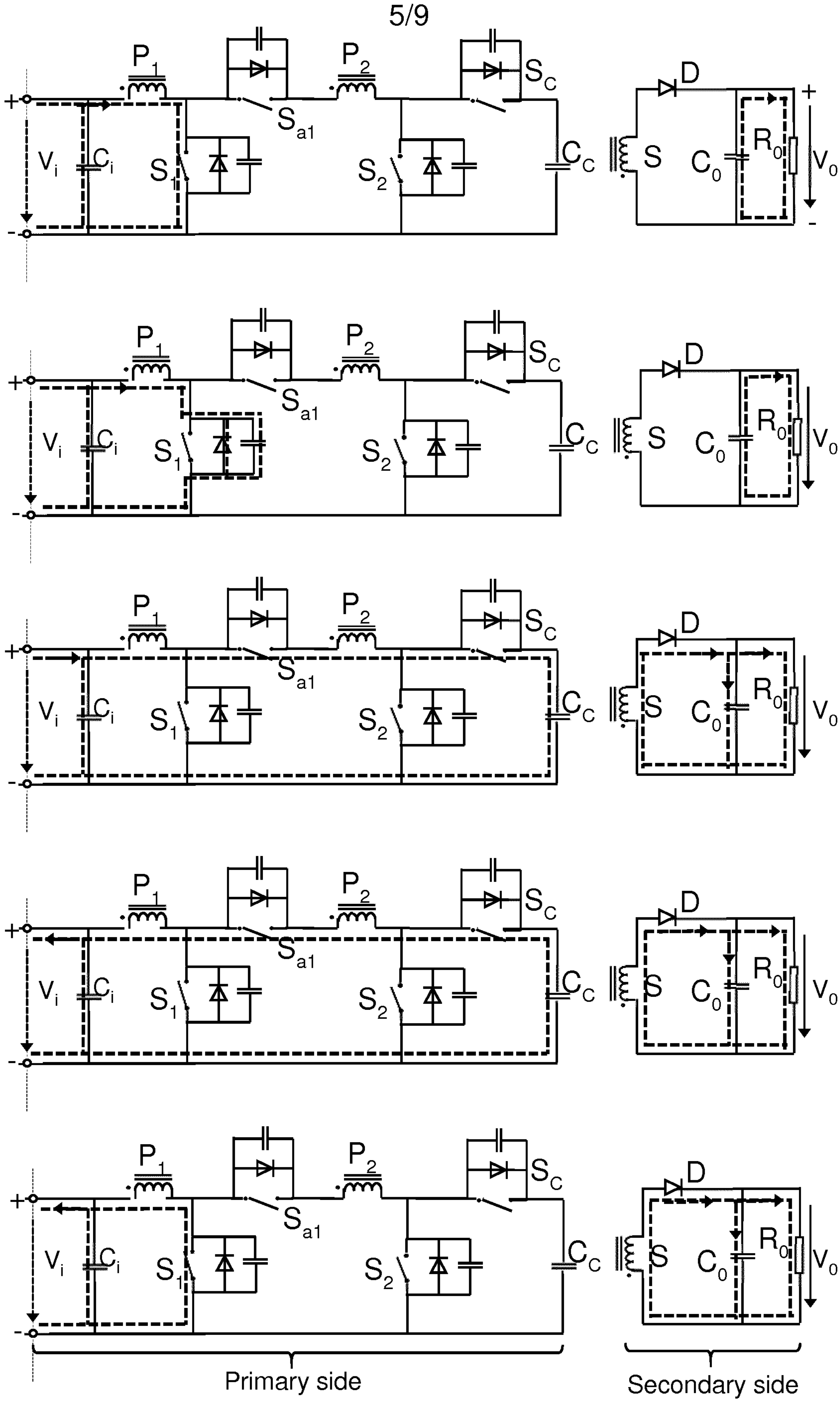
P1
P2
Sa1
SC
S1
S2
Vi
Ci
CC
D
S
C0
R0
V0
+
-
Primary side
Secondary side

FIG. 7

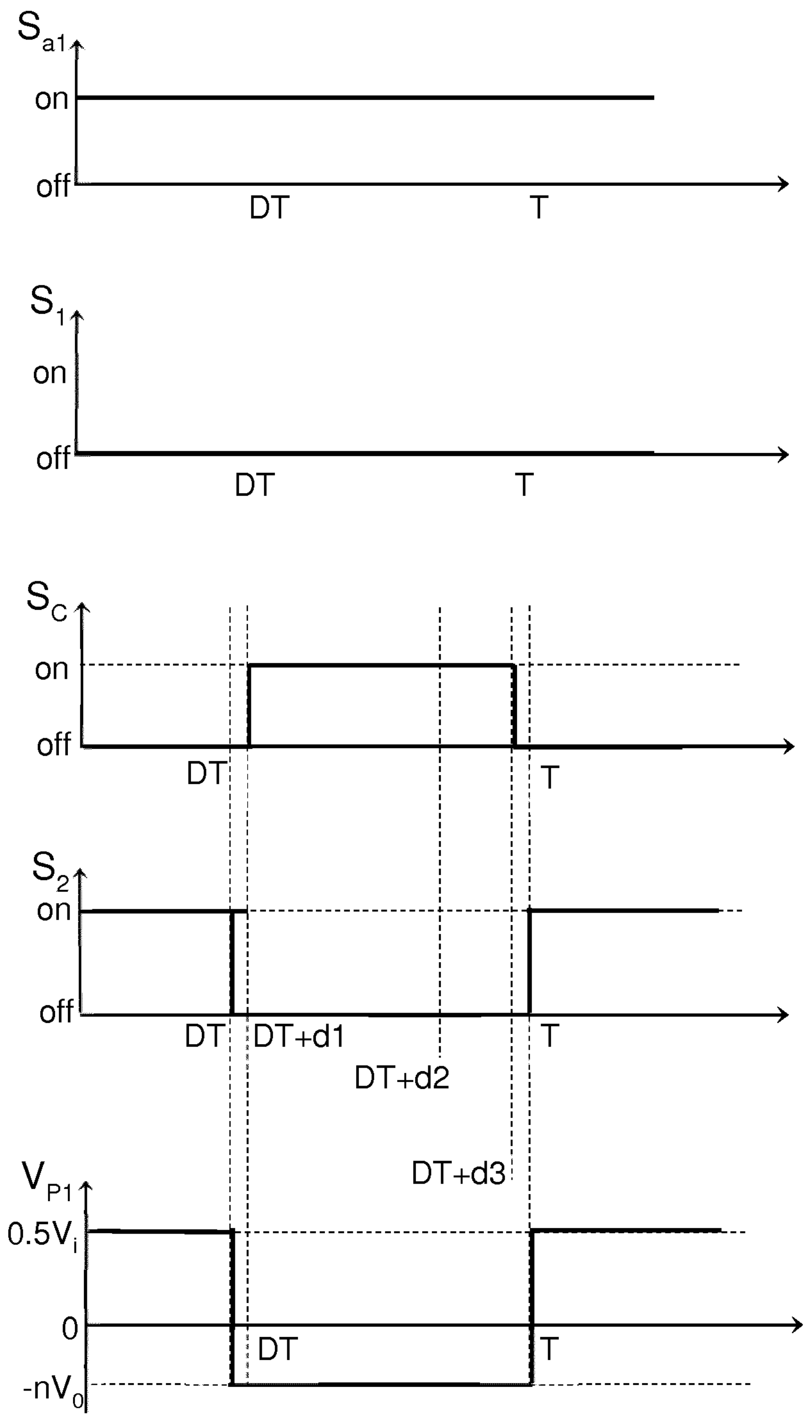
S_a1
on
off
DT
T
S_1
on
off
DT
T
S_C
on
off
DT
T
S_2
on
off
DT
DT+d1
DT+d2
DT+d3
T
V_P1
0.5V_i
0
-nV_0
DT
T

FIG. 8

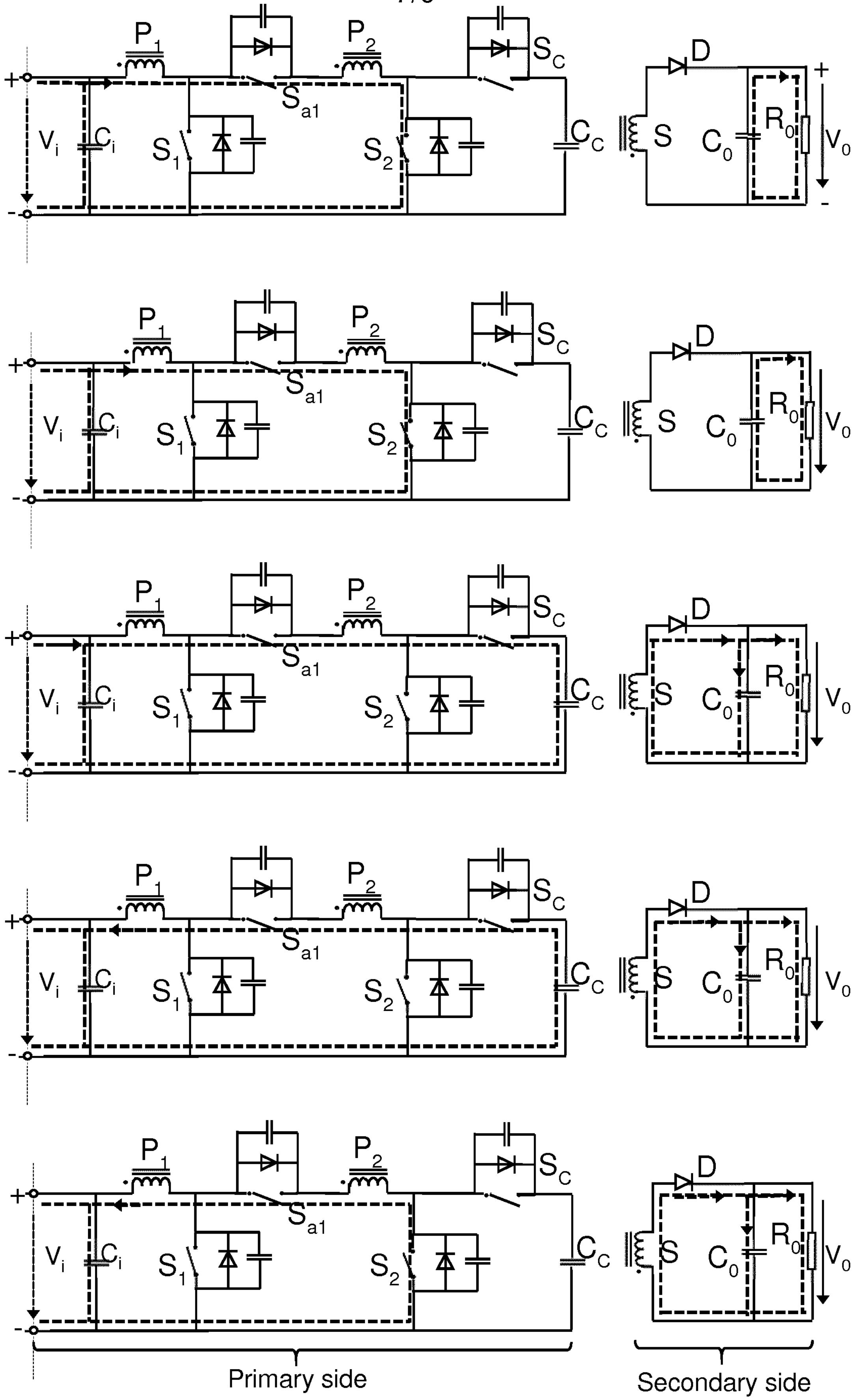
P1
P2
Sa1
SC
D
Vi
Ci
S1
S2
CC
S
C0
R0
V0
+
-
Primary side
Secondary side

FIG. 9

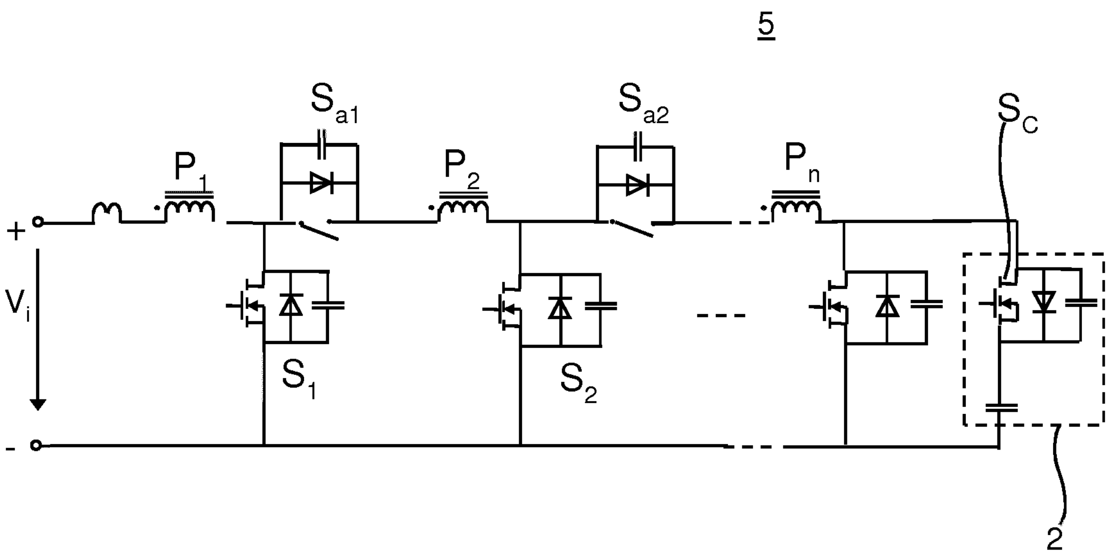

FIG. 10

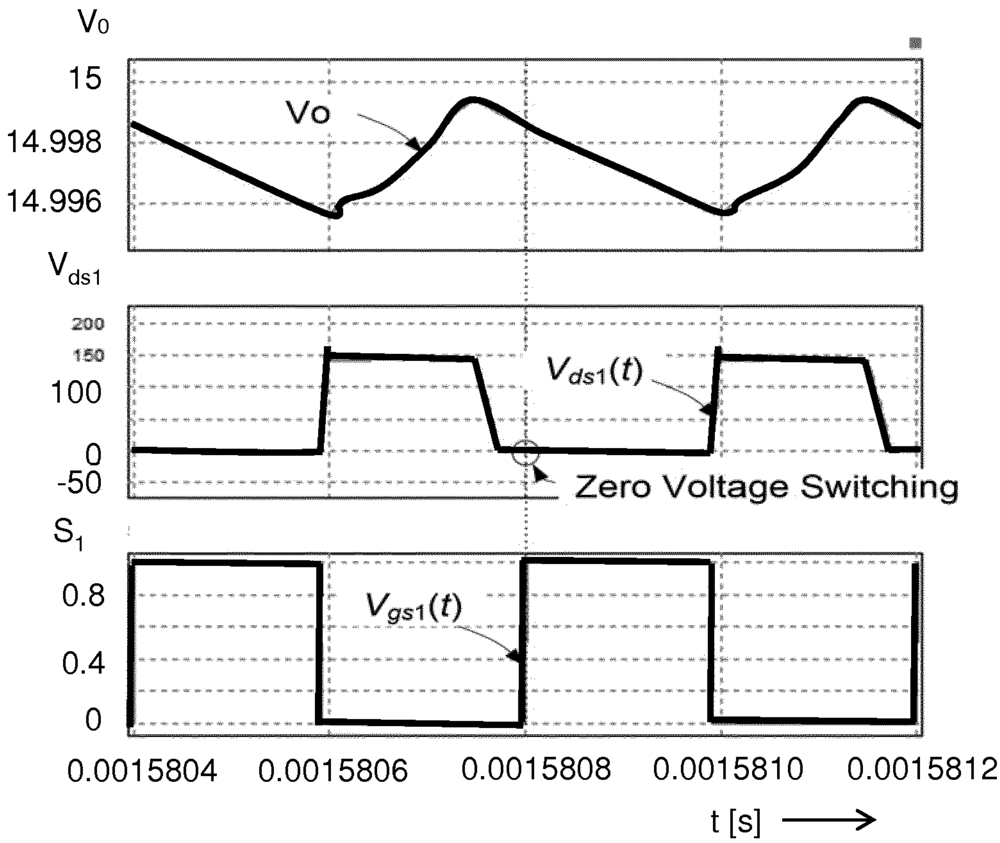

FIG. 11A

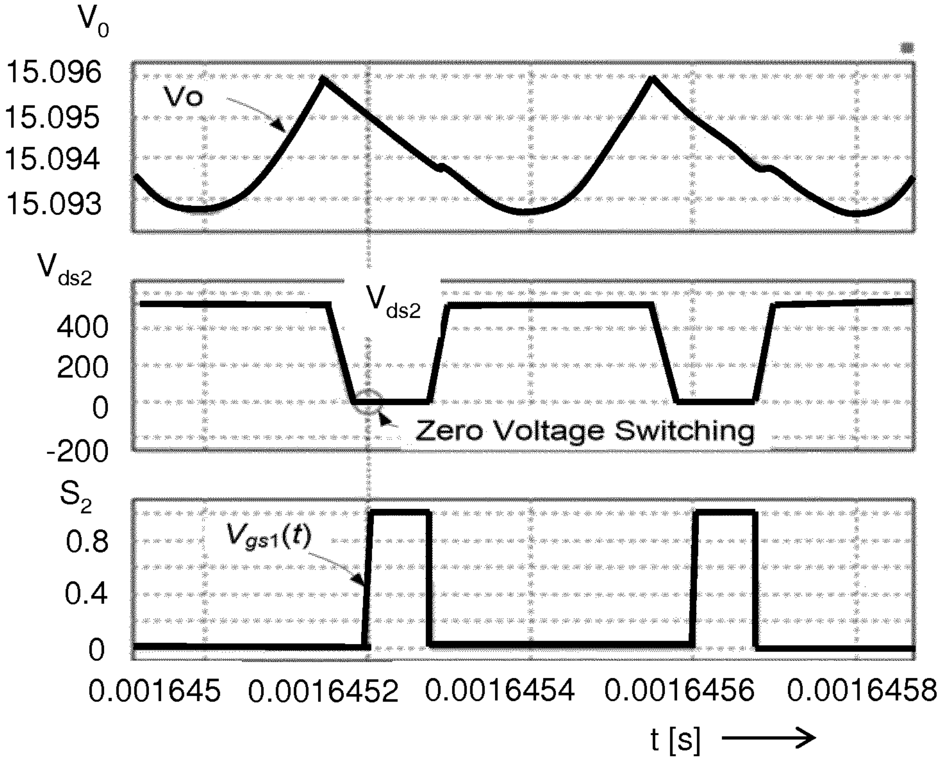

FIG. 11B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/082108

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M3/335
ADD. H02M1/00 H02M1/34

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

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CN 101 174 797 A (POWER HANGZHOU CO LTD E [CN]) 7 May 2008 (2008-05-07) abstract figures 1-7 page 8 paragraph [0002] -----	1-10
A	US 2013/279208 A1 (LAI YUAN-FANG [TW] ET AL) 24 October 2013 (2013-10-24) abstract figures 2, 4 paragraph [0003] ----- -/--	1-10

[X] Further documents are listed in the continuation of Box C.

[X] 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
28 January 2020	11/02/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Adami, Salah-Eddine

1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/082108

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	KI-BUM PARK ET AL: "Series-Input Series-Rectifier Interleaved Forward Converter With a Common Transformer Reset Circuit for High-Input-Voltage Applications", IEEE TRANSACTIONS ON POWER ELECTRONICS, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, USA, vol. 26, no. 11, 1 November 2011 (2011-11-01), pages 3242-3253, XP011369868, ISSN: 0885-8993, DOI: 10.1109/TPEL.2011.2148126 abstract shared clamp; figure 5b Section III.C -----	1-10
A	US 5 808 879 A (LIU RUI [US] ET AL) 15 September 1998 (1998-09-15) abstract figures 1a, 1b -----	1-10
Y	WO 2012/155325 A1 (INTERSIL INC [US]; YANG SHIJIA [CN] ET AL.) 22 November 2012 (2012-11-22) abstract figures 1-8 paragraph [0004] paragraph [0014] -----	1-10
Y	US 2016/087541 A1 (XIE RENJIAN [CN] ET AL) 24 March 2016 (2016-03-24) abstract figure 1 paragraph [0015] -----	1-10

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/082108

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
CN 101174797	A	07-05-2008	NONE			
US 2013279208	A1	24-10-2013	TW	201345131	A	01-11-2013
			US	2013279208	A1	24-10-2013
US 5808879	A	15-09-1998	DE	69719945	D1	24-04-2003
			DE	69719945	T2	22-01-2004
			EP	0851566	A2	01-07-1998
			US	5808879	A	15-09-1998
WO 2012155325	A1	22-11-2012	NONE			
US 2016087541	A1	24-03-2016	CN	105471245	A	06-04-2016
			US	2016087541	A1	24-03-2016