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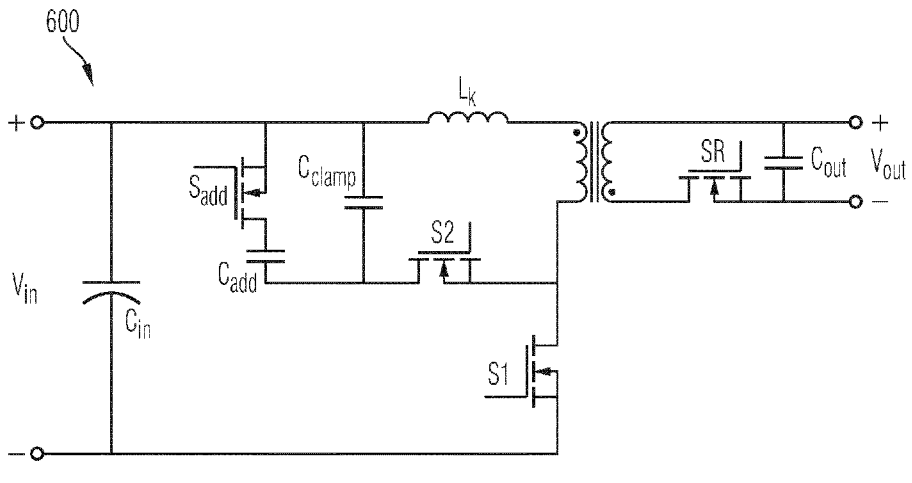
(54) **Title:** ACTIVE CLAMP FLYBACK CONVERTER WITH VARIABLE RESONANCE FREQUENCY

Fig. 6A



(57) **Abstract:** An active clamp flyback, ACF, converter (600; 610; 700; 710; 720; 900; 1020) comprises a switchable clamp circuit (Lk, S2, Cclamp; Lk,p, S2, Cclamp) arranged on an input side of the ACF converter, and a tank capacitor (Cclamp; Cout) configured to form, in combination with a leakage inductance (Lk; Lk,p, Lk,s) of the ACF converter, a resonator, when the clamp circuit is switched on. The ACF converter further comprises at least one additional capacitor (Cadd), and the resonator is switchable between a first switching state, in which the additional capacitor (Cadd) is connected to the resonator, and a second switching state, in which the additional capacitor (Cadd) is disconnected from the resonator, wherein a capacitance of the resonator is variable dependent on the switching state of the resonator.

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Active Clamp Flyback Converter with Variable Resonance Frequency

TECHNICAL FIELD

[1] This specification refers to embodiments of an active clamp flyback converter, to embodiments of a control system comprising an active clamp flyback converter and a control unit, and to embodiments of operating an active clamp flyback converter.

BACKGROUND

[2] Many functions of modern devices in automotive, consumer and industrial applications, such as converting electrical energy and driving an electric motor or an electric machine, rely on power semiconductor devices. For example, Insulated Gate Bipolar Transistors (IGBTs), Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and diodes, to name a few, have been used for various applications including, but not limited to, switches in power supplies and power converters.

[3] For example, such power converter is a flyback converter, which typically employs a MOSFET as a switching element.

[4] A flyback converter (German: “Sperrwandler”) converts an input voltage into an output voltage and provides a galvanic isolation between these voltages by means of a transformer.

[5] Known flyback converters can be divided into types based on the applied operation principle. A first type is based on a continuous conduction mode (CCM), wherein the transformer has a residual energy when the switching element is turned on. A second type is based on a discontinuous conduction mode (DCM), wherein the transformer has substantially no energy when the switching element is turned on. Moreover, active clamp flyback (ACF) converters have been conceived to compensate for a leakage inductance of the converter by storing the energy in a switchable active clamp.

[6] The present specification relates to said active clamp flyback (ACF) converters.

SUMMARY

[7] According to an embodiment, an active clamp flyback, ACF, converter is presented. The ACF converter comprises a switchable clamp circuit arranged on an input side of the ACF converter, and a tank capacitor configured to form, in combination with a leakage inductance of the ACF converter, a resonator, when the clamp circuit is switched on, wherein the ACF converter further comprises at least one additional capacitor, and the resonator is switchable between a first switching state, in which the additional capacitor is connected to the resonator, and a second switching state, in which the additional capacitor is disconnected from the resonator, wherein a capacitance of the resonator is variable dependent on the switching state of the resonator.

[8] According to a further embodiment, a further active clamp flyback, ACF, converter is presented. The ACF converter comprises a switchable clamp circuit arranged on an input side of the ACF converter, and a tank capacitor configured to form, in combination with a leakage inductance of the ACF converter, a resonator, when the clamp circuit is switched on. The ACF converter is configured to be operated at any of at least a first output voltage and a second output voltage at a same primary peak-to-peak current, and a capacitance of the resonator is variable dependent on the output voltage, wherein the first output voltage and the second output voltage differ by at least a factor of 2, and the capacitance of the resonator varies in accordance with a voltage-dependent capacitance of the tank capacitor such that between any of the output voltages a proportion of half a resonance period of the resonator to a demagnetization time of the ACF converter varies by less than a factor of 1.3.

[9] According to a yet further embodiment, an active clamp flyback, ACF, converter control system is presented. The ACF converter control system comprises an ACF

converter as herein described and a control unit connected to the ACF converter. The control unit is configured to determine an output voltage of the ACF converter; determine, based on the output voltage, a designated switching state of the resonator of the ACF converter; generate a switching signal for the resonator in accordance with the designated switching state, and output the switching signal towards the ACF converter.

[10] According to a yet further embodiment, a method of operating an active clamp flyback, ACF, converter is presented. The ACF converter comprises a switchable clamp circuit arranged on an input side of the ACF converter; a tank capacitor configured to form, in combination with a leakage inductance of the ACF converter, a resonator, when the clamp circuit is switched on, and at least one additional capacitor, wherein the resonator is switchable between a first switching state, in which the additional capacitor is connected to the resonator, and a second switching state, in which the additional capacitor is disconnected from the resonator, wherein a capacitance of the resonator is variable dependent on the switching state of the resonator. The method comprises determining an output voltage of the ACF converter; determining, based on the output voltage, a designated switching state of the resonator of the ACF converter; generating a switching signal for the resonator in accordance with the designated switching state, and outputting the switching signal towards the ACF converter.

[11] Those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[12] The parts in the figures are not necessarily to scale, instead emphasis being placed upon illustrating principles of the invention. Moreover, in the figures, like reference numerals may designate corresponding parts. In the drawings:

[13] Fig. 1 schematically and exemplarily illustrates an active clamp flyback, ACF, converter in accordance with an example;

[14] Figs. 2A - 2B schematically and exemplarily illustrate for different output voltages waveforms of an ACF converter during a switching cycle in accordance with an example;

[15] Fig. 3 schematically and exemplarily illustrates an active clamp flyback, ACF, converter in accordance with one or more embodiments;

[16] Fig. 4 schematically and exemplarily illustrates graphs of a voltage dependent capacitance of differently configured capacitors in accordance with one or more embodiments;

[17] Fig. 5 schematically and exemplarily illustrates an active clamp flyback, ACF, converter in accordance with one or more embodiments;

[18] Figs. 6A – 7C schematically and exemplarily illustrate active clamp flyback, ACF, converters in accordance with various embodiments;

[19] Fig. 8 schematically and exemplarily illustrates an active clamp flyback, ACF, converter in accordance with one or more embodiments; and

[20] Fig. 9 schematically and exemplarily illustrates an active clamp flyback, ACF, converter in accordance with one or more embodiments.

DETAILED DESCRIPTION

[21] In the following detailed description, reference is made to the accompanying drawings which form a part hereof and in which are shown by way of illustration specific embodiments in which the invention may be practiced.

[22] In this regard, directional terminology, such as “top”, “bottom”, “below”, “front”, “behind”, “back”, “leading”, “trailing”, “above” etc., may be used with reference to the orientation of the figures being described. Because parts of embodiments can be positioned in a number of different orientations, the directional terminology is used for purposes of illustration and is in no way limiting. It is to be understood that other embodiments may be utilized and structural or logical changes may be made without departing from the scope of the present invention. The following detailed description, therefore, is not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims.

[23] Reference will now be made in detail to various embodiments, one or more examples of which are illustrated in the Figures. Each example is provided by way of explanation, and is not meant as a limitation of the invention. For example, features illustrated or described as part of one embodiment can be used on or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the present invention includes such modifications and variations. The examples are described using

specific language which should not be construed as limiting the scope of the appended claims. The drawings are not scaled and are for illustrative purposes only. For clarity, the same elements or manufacturing steps have been designated by the same references in the different drawings if not stated otherwise.

[24] In the context of the present specification, the terms “in ohmic contact”, “in electric contact”, “in ohmic connection”, and “electrically connected” intend to describe that there is a low ohmic electric connection or low ohmic current path between two regions, sections, zones, portions or parts of the device described herein. Further, in the context of the present specification, the term “in contact” intends to describe that there is a direct physical connection between two elements of the respective semiconductor device; e.g., a transition between two elements being in contact with each other may not include a further intermediate element or the like.

[25] In addition, in the context of the present specification, the term “electric insulation” is used, if not stated otherwise, in the context of its general valid understanding and thus intends to describe that two or more components are positioned separately from each other and that there is no ohmic connection connecting those components. However, components being electrically insulated from each other may nevertheless be coupled to each other, for example mechanically coupled and/or capacitively coupled and/or inductively coupled. To give an example, two electrodes of a capacitor may be electrically insulated from each other and, at the same time, mechanically and capacitively coupled to each other, e.g., by means of an insulation, e.g., a dielectric.

[26] Fig. 1 shows schematically an active clamp flyback, ACF, converter 100. At an input, or: primary, side of the ACF converter 100 an input voltage V_in is applied. The input voltage V_in becomes converted by the ACF converter 100 into an output voltage V_out provided at an output, or: secondary, side of the ACF converter 100. A transformer of the ACF converter 100 provides for a galvanic isolation between the primary side and the secondary side. A current through the primary side is switchable by means of the primary side switch S1. Further arranged on the primary side is a clamp circuit, comprising a primary winding of the transformer, leakage inductance L_k, a clamp circuit switch S2 and a clamp capacitance C_clamp. On the secondary side of the ACF converter 100, a current is switchable by means of a synchronous rectifier SR or diode, which serves for reducing conduction losses. Further arranged on the primary and the secondary sides are capacitors C_in and C_out.

[27] Operation of the ACF converter 100 will be described with reference to Figs. 1 and 2A. The waveforms shown in Fig. 2A correspond exemplarily to an operation of the ACF converter 100 with a nominal power P_out = 65 W, a constant output voltage V_out = 20 V at full-load and V_in = 90 V_rms.

[28] During a first phase, t0 – t1, the switch S1 is in an on-position, while switches S2 and SR are in an off-position. The positive voltage V_in forces the same current through the magnetizing inductance L_m of the transformer and the leakage inductance L_k. No current is flowing through the secondary side, since the SR is switched off. For example, a body diode of the SR is blocking a voltage equal to V_out + V_in / n, where n is the transformer turn-ratio. During the first phase, the primary side current follows Equation (1):

$$I_{Lm}(t) = I_{Lk}(t) = I_{Lm}(t_0) + \frac{V_{in}}{L_m + L_k}(t - t_0) \qquad (1)$$

[29] During a second phase, t1 – t2, all switches are off. The magnetizing current remains positive, discharging the parasitic capacitance of the switch S2. This enables subsequent zero voltage switching (ZVS) for the switch S2.

[30] During a third phase, t2 – t3, switch S2 becomes switched on under ZVS, while all other switches are off. As soon as the primary side voltage reaches a value slightly higher than the reflected voltage n * V_out, the body diode of the SR starts to conduct current and resonance between the leakage inductance L_k and the clamp capacitor C_clamp occurs. The resonance frequency of the oscillation follows Equation (2):

$$f_{res} = \frac{1}{2\pi\sqrt{L_k C_{clamp}}} \qquad (2)$$

[31] At the same time, the magnetizing inductance is discharging with a current equal to Equation (3):

$$I_{Lm}(t) = I_{Lm}(t_2) - \frac{nV_{out}}{L_m}(t - t_2) \qquad (3)$$

[32] The current flowing through the secondary side SR is equal to the difference between the magnetizing current I_Lm and the leakage current I_Lk, as expressed by Equation (4):

$$I_{SR}(t) = n(I_{Lm}(t) - I_{Lk}(t)) \qquad (4)$$

[33] When I_Lk(t) = I_Lm(t), the secondary side current equals zero and the SR can be turned off under zero current switching (ZCS). To ensure ZVS and ZCS operation at the same time, the leakage current I_Lk needs to intersect the magnetizing current I_Lm while the latter is negative enough to be able to completely discharge a parasitic capacitance seen at a drain node of the primary side switch S1. Optimal operation is achieved when the intersection happens at the minimal amount of negative magnetizing current needed to discharge the parasitic capacitance seen at the drain node of the primary side switch S1.

[34] During a fourth phase, t3 – t4, all switches are off. The magnetizing current remains negative, discharging the parasitic capacitance seen at the drain node of the primary side switch S1. This enables subsequent zero voltage switching (ZVS) for lossless turn-on of the switch S1 in the next phase. Once the parasitic capacitance seen at the drain node of the primary side switch S1 has been completely discharged, a new switching cycle can begin, with a ZVS turn-on of switch S1.

[35] Zero current switching (ZCS) operation for the SR is desirable to enable a lossless turn-off of the device. When a single constant output voltage is synthesized by means of the ACF converter 100, it is possible to ensure ZCS for all load and input voltage conditions using a variable switching frequency control where the off-time of the main switch S1 is constant throughout different load and input voltage conditions. Accordingly, ACF converters are often designed to supply a single constant output voltage which the converter operation is optimized for. Output voltage regulation is achieved with such devices by varying the on-time of the main switch S1. The off-time is selected such as to ensure ZVS and ZCS when the switching frequency of the converter is at its minimum value, corresponding to a minimum input voltage and full-load conditions. Selecting the off-time in this way ensures that also for all other input voltage and load conditions ZVS and ZCS operation is achieved.

[36] However, a drawback of this control strategy is that the amount of reactive current circulating in the converter is not minimized. For high input voltages and light loads the magnetizing current I_Lm reaches a negative peak which, in absolute value, is higher than the one reached for low input voltages and heavy loads. Consequence of this is an increase of the circulating current (reactive current) at high input voltage/light load conditions.

[37] Furthermore, if the output voltage is not fixed anymore, the slope of the magnetizing current during the demagnetizing phase varies depending on the selected

output voltage (dI / dt = - n * V_out / L_m). As a consequence, if the same off-time is used the following problems may arise. ZVS for the primary side main switch S1 may be lost, ZCS for the secondary side synchronous rectifier SR may be lost, and a high rms value of the secondary side current may occur.

[38] As an example, Fig. 2B shows waveforms corresponding to an operation of the same converter design as in Fig. 2A but with an output voltage V_out = 10 V instead of 20 V, with V_in = 90 V_rms and P_out = 40 W. It can be seen that both ZVS and ZCS are no longer achieved. Although ZVS operation could be restored by simply increasing the off time in order for the negative magnetizing current to be sufficient to completely discharge the parasitic capacitance of S1, this would even increase the current value at which SR is turned off. Moreover, Fig. 2B shows that the rms values of the leakage current and the SR current are not optimized, as lower rms current values enable higher efficiency.

[39] Fig. 3 shows schematically an ACF converter 300 for use with different output voltages. Unless stated otherwise in the following, the design of the ACF converter 300 corresponds to the design of the ACF converter 100 shown in Fig. 1. Moreover, the ACF converter 300 is configured to be operated with switching cycles having switching phases analogous to those described above. Different from the previous examples, the ACF converter 300 comprises in the clamp circuit a clamp capacitor C_clamp_var with variable capacitance. Particularly, the capacitance of the clamp capacitor C_clamp_var is variable in accordance with a variation in the output voltage V_out.

[40] The resonance frequency of the tank circuit formed by the leakage inductance L_k and the clamp capacitor C_clamp_var is defined by Equation 2. Meanwhile, the demagnetization time t_demag of the magnetizing inductance L_m follows Equation 5, where I_ppk stands for the primary peak-to-peak current and which involves the output voltage V_out:

$$t_{demag} = \frac{L_m I_{ppk}}{n V_{out}} \qquad (5)$$

[41] To achieve ZCS, ZVS and optimised RMS values for the SR current and the leakage current I_k, an intersection in the waveforms between leakage current and magnetizing current should occur as close as possible to the negative peak of the latter. For this to happen, the demagnetization time of the magnetizing inductance, t_demag, and the resonance frequency of the resonator, f_res, need to at least closely fulfil Equation 6:

$$t_{demag} = \frac{1}{2f_{res}} \quad (6)$$

[42] Accordingly, the variation in t_demag due to variation in the output voltage V_out may be compensated for by a corresponding variation of f_res. Yet, the leakage inductance value results from the overall transformer design, comprising leakage on the primary and the secondary sides which affect each other across the transformer, and therefore can hardly be designed exactly in an adjustable manner. At the same time the clamp capacitance provides a more suitable parameter for optimising the resonance frequency f_res in accordance with variable output voltage V_out.

[43] As will be appreciated, Equation 7 does not need to be exactly fulfilled for an advantageous operation of an ACF converter. Nonetheless, practical considerations, e.g., taking into account the need to ensure ZVS and other second-order effects, confine the length of half the resonance period T_res to be within the range 0.5 to 1.5 times the demagnetization time t_demag, as expressed by Equation 7:

$$\frac{1}{2}t_{demag} \leq \frac{T_{res}}{2} \leq \frac{3}{2}t_{demag} \quad (7)$$

[44] It will further be appreciated that variations in the output voltage V_out will translate into a variation of the switching frequency. In particular, lower output voltages correspond to lower switching frequencies. This means that also a lower tank resonance frequency, hence a higher clamp capacitance value, is desirable if a fixed leakage inductance is assumed.

[45] In accordance with the above, in some examples the ACF converter 300 is configured to be operated optionally at different output voltages. At the same time the clamp capacitance C_clamp_var is configured to exhibit a voltage dependent capacitance, such that with a constant primary peak-to-peak current and a difference between at least two optional output voltages by a factor of 2, a proportion between half the resonance period of the resonator and the demagnetization time t_demag of the ACF converter 300 varies by less than a factor of 1.5. For example, the proportion between half the resonance period of the resonator and the demagnetization time t_demag varies by less than 1.4, particularly by less than 1.3, more particularly by less than 1.2.

[46] In some examples, the clamp capacitor C_clamp_var comprises a ceramic capacitor. Many ceramic capacitors exhibit a voltage dependent capacitance. Thus, a suitably configured ceramic capacitor facilitates in some examples a functionality of the ACF converter 300 as described above.

[47] Fig. 4 shows schematically examples of a voltage dependency of the capacitance of differently configured ceramic capacitors over a voltage range from 0 to 25 V. As is apparent from Fig. 4, given a predetermined peak-to-peak current and optional output voltages for which the ACF converter 300 is designed to be operated at, the capacitor C_clamp_var for the ACF converter 300 can be advantageously configured. It follows from Equations 5 and 6 that a capacitance of the clamp capacitor C_clamp_var at a second output voltage V_out2 ideally varies relative to the capacitance of C_clamp_var at the first output voltage V_out1 in accordance with the following Equation 8:

$$C_2 = C_1 \left(\frac{V_{out1}}{V_{out2}}\right)^2 \quad (8)$$

[48] A larger output voltage V_out thus requires a smaller capacitance in the resonator, which is in agreement with the voltage dependencies shown in Fig. 4. In addition, a proportionality of the capacitance to the squared inverse of the output voltage, as defined in Equation 9, can be approximated, for example, over a substantial voltage range by means of a convex curve segment in each of the capacitance plots in Fig. 4. For example, a suitable curve segment extends for the capacitor over a voltage range whose maximal and minimal output voltages differ by at least a factor of 1.5, for example by at least a factor of 1.7, particularly by at least a factor of 2, more particularly by at least a factor of 2.5.

[49] Fig. 5 shows schematically an ACF converter 500. The ACF converter 500 is a modification of the ACF converter 300 of Fig. 3. Unless otherwise clear from the following, the above statements on Figs. 3 and 4 apply correspondingly regarding a structure and a functionality of the ACF converter 500.

[50] Different from the ACF converter 300, where the clamp circuit is connected to the high potential side of the input voltage V_in, the ACF converter 500 comprises a clamp circuit connected to the low potential side, e.g., ground. The ACF converter 300 thus comprises a high-side clamp, whereas the ACF converter 500 comprises a low-side clamp. As a particularity of the low-side clamp of the ACF converter 500, a DC voltage applied across the clamp capacitor C_clamp_var equals approximately the sum of the input voltage

V_in and reflected output voltage n * V_out, hence the resonance frequency f_res is dependent not only on the output voltage V_out but also on the input voltage V_in, which needs to be considered in the configuring of the clamp capacitor C_clamp_var.

[51] Figs. 6A and 6B schematically show further embodiments of ACF converters 600, 610 having a variable capacitance in a clamp circuit, for example, for operation at different output voltages.

[52] Fig. 6A shows schematically an ACF converter 600. The design of the ACF converter 600 resembles that of the ACF converter 300 of Fig. 3. However, different from the ACF converter 300, the ACF converter 600 comprises an additional capacitor C_add and an additional switch S_add. By means of the additional switch S_add the additional capacitor C_add can be connected to or disconnected from a resonator comprising the leakage inductance L_k and the clamp capacitor C_clamp. In the example shown in Fig. 6A, when the additional switch S_add is in an on-position the additional capacitor C_add is connected parallel to the clamp capacitor C_clamp thereby adding to the capacitance in the resonator. Thus, by operation of the additional switch S_add, a capacitance of the resonator in the clamp circuit is switchable between the capacitance of the clamp capacitor C_clamp alone and, alternatively, the sum of the capacitance of each of the capacitors C_clamp and C_add. The capacitance in the resonator may be switched, for example, to provide for an improved resonance frequency f_res in accordance with an operation of the ACF converter 600 at either of two different output voltages or different output voltage ranges.

[53] In some examples, one or both of the capacitors C_clamp, C_add exhibit a voltage dependent capacitance. In these examples, switching the additional switch S_add is further performed in accordance with the output voltage based on the voltage dependent capacitance of the one or both of the capacitors C_clamp, C_add.

[54] Fig. 6B shows schematically an ACF converter 610. Different from the ACF converter 600, in the ACF converter 610 the additional capacitor C_add and the additional switch S_add are arranged such that the additional capacitor C_add is connected in series to the clamp capacitor C_clamp by operation of the additional switch S_add. Specifically, by switching the additional switch S_add into an off-position, a current in the clamp circuit is forced to pass through the additional capacitor C_add, which is connected in series to the resonator in the clamp circuit. Conversely, by switching the additional switch S_add into an on-position, the additional capacitor C_add becomes shorted, thus excluded from

the resonator, such that C_add effectively does not contribute to the capacitance in the resonator.

[55] Figs. 7A to 7C schematically show ACF converters 700, 710, 720 in accordance with further embodiments. Similar to the embodiments in Figs. 6A and 6B, the embodiments in Figs. 7A to 7C show ACF converters with switchable resonators. Different from the preceding examples, however, where the clamp circuit is connected to a high potential side of the input voltage V_in, the embodiments in Figs. 7A to 7C comprise clamp circuits connected to a low potential side, thereby forming low-side clamps, analogous to the ACF converter 500 of Fig. 5.

[56] Fig. 7A shows schematically an ACF converter 700 similar to the ACF converter 600 of Fig. 6A. In particular, by switching the additional switch S_add, a capacitance of the resonator in the clamp circuit is changed in accordance with the additional capacitor C_add being connected to the resonator in parallel to the clamp capacitor C_clamp or being disconnected from the resonator. In this arrangement, the control signal of S_add needs to be the same as that of S2, meaning that also S_add is switched on and off at high frequency during operation. This leads to increased switching losses. However, an advantage of this configuration lies in that S_add, S1 and S2 are all referenced to the primary side low potential, or ground, hence there is no need for any high-side driver. In some examples, S_add is an n-type switch, whereas S2 is a p-type switch.

[57] Fig. 7B shows schematically an ACF converter 710 according to another embodiment. The ACF converter 710 differs from the ACF converter 700 in that also the additional capacitor C_add is connected to and disconnected from the low potential node by the switch S2, simultaneously with the clamp capacitor C_clamp. In this manner, increased switching losses as with the ACF converter 700 are avoided. As a drawback, the additional switch S_add is not referenced to the low potential, or ground. In some examples, S_add is an n-type switch, whereas S2 is a p-type switch.

[58] Fig. 7C shows an ACF converter 720 according to another embodiment. Analogous to the converter in Fig. 6B, the ACF converter 720 comprises an additional capacitor C_add that is switchable by means of the additional switch S_add to become connected in series to the clamp capacitor C_clamp. For example, S_add is an n-type switch, whereas S2 is a p-type switch. Also in the embodiment of Fig. 7C increased switching losses are avoided, since the additional switch S_add remains in the same

position during operation of the ACF converter 720 once the latter has been adjusted, e.g., to an intended output voltage.

[59] Fig. 8 shows schematically an ACF converter 800 according to another embodiment. The design of the ACF converter 800 resembles that of Fig. 3. However, different from the ACF converter 300, a variable capacitance C_out_var is arranged on the secondary side of the ACF converter 800. Due to leakage reflectance via the transformer of the ACF converter 800, a leakage inductance L_k in the clamp circuit arises from a leakage inductance of the primary side L_k,p as well as a leakage inductance of the secondary side L_k,s. If the clamp capacitor C_clamp is chosen sufficiently large so as to produce a resonance frequency on the primary side which is much lower than a switching frequency of the ACF converter 800, the resonance frequency f_res of the tank is mainly determined by the capacitance on the output side, as described by the Equation 9:

$$f_{res} = \frac{1}{2\pi\sqrt{\left(\frac{L_{k,p}}{n^2}+L_{k,s}\right)C_{out}}} \qquad (9)$$

[60] Using Equation 9 in place of Equation 5, for determining the desired output capacitance C_out for different output voltages, the techniques described above in connection with Figs. 3 and 4 can be applied analogously. In particular, the output capacitor C_out is advantageously configured to exhibit a suitable voltage dependency of its capacitance in accordance with different optional output voltages.

[61] Among the advantages of the ACF converter 800, reduced current values for SR, S2 and the primary side of the transformer as well as optimised SR behavior can be achieved. However, typically a high voltage ripple occurs on C_out, which needs to be filtered out, for example, by means of an additional LC filter stage, as shown in Fig. 8 by L_f and C_f.

[62] Fig. 9 shows schematically an ACF converter 900 according to another embodiment. Similar to the example of Fig. 8, the ACF converter 900 provides for a variable capacitance on the secondary side. Analogously to the examples in Figs. 6A to 7C, the capacitance in the resonator is switchable by means of a switchable additional capacitor C_add.

[63] While Figs. 8 and 9 show ACF converters with high-side clamps, variations of the shown embodiments have low-side clamps. It will further be appreciated that other

embodiments of the ACF converter 900 comprise a switchable additional capacitor arranged in series to the output capacitor C_out, analogously to Fig. 6B.

[64] Fig. 10 shows an ACF converter control system 1000 according to an embodiment. The ACF converter control system 1000 comprises a control unit 1010 and an ACF converter 1020 that is switchable by means of the control unit 1010.

[65] In some examples, the ACF converter 1020 comprises a switchable ACF converter as described above, in connection with any one of Figs. 5 to 7C and 9. In further examples, the control unit is configured to switch the ACF converter 1020 between different switching states of a tank resonator of the ACF converter 1020, wherein the different switching states correspond to different capacitance values present in the tank resonator. In further examples, the control unit 1010 is configured to switch the ACF converter 1020 in accordance with different output voltages intended for an operation of the ACF converter 1020.

[66] In some of the aforementioned examples, the control unit is configured to determine an output voltage of the ACF converter and to determine, based on the output voltage, the designated switching state of the resonator of the ACF converter 1020. It is further configured to generate a switching signal for the resonator in accordance with the designated switching stage, and output the switching signal towards the ACF converter 1020. For example, determining the designated switching state of the resonator based on the output voltage is performed by accessing a mapping table in which different voltages or voltage ranges are associated with different switching states of the ACF converter 1020.

[67] In the above examples, ACF converters with switchable resonators have been described in which a capacitance of the tank resonator is switchable between two switching states. However, it will be appreciated that other embodiments comprise ACF converters that are switchable between more than two switching states, for example, including two or more additional capacitors C_add that may, individually or groupwise, be switched to become connected to or disconnected from the resonator, in accordance with an intended output voltage.

[68] Fig. 11 shows schematically a flow diagram of a method 1100 of operating an active clamp flyback converter. The method 1100 is intended to be used with an ACF converter, e.g., as described in connection with Figs. 6A to 7C and 9. The method 1100 can be performed, e.g., by means of the ACF converter control system 1000 of Fig. 10.

The method 1100 comprises determining an output voltage of the ACF converter, block 1110; determining, based on the output voltage, the designated switching state of the resonator of the ACF converter, block 1120; generating a switching signal for the resonator in accordance with the designated switching state, block 1130; and outputting the switching signal towards the ACF converter, block 1140.

[69] Spatially relative terms such as "under", "below", "lower", "over", "upper" and the like, are used for ease of description to explain the positioning of one element relative to a second element. These terms are intended to encompass different orientations of the respective device in addition to different orientations than those depicted in the Figures. Further, terms such as "first", "second", and the like, are also used to describe various elements, regions, sections, etc. and are also not intended to be limiting. Like terms refer to like elements throughout the description.

[70] As used herein, the terms "having", "containing", "including", "comprising", “exhibiting” and the like are open ended terms that indicate the presence of stated elements or features, but do not preclude additional elements or features.

[71] With the above range of variations and applications in mind, it should be understood that the present invention is not limited by the foregoing description, nor is it limited by the accompanying drawings. Instead, the present invention is limited only by the following claims and their legal equivalents.

* * * * *

CLAIMS

1. An active clamp flyback, ACF, converter (600; 610; 700; 710; 720; 900; 1020) comprising:
   - a switchable clamp circuit (Lk, S2, Cclamp; Lk,p, S2, Cclamp) arranged on an input side of the ACF converter, and
   - a tank capacitor (Cclamp; Cout) configured to form, in combination with a leakage inductance (Lk; Lk,p, Lk,s) of the ACF converter, a resonator, when the clamp circuit is switched on,

   wherein the ACF converter further comprises at least one additional capacitor (Cadd), and the resonator is switchable between a first switching state, in which the additional capacitor (Cadd) is connected to the resonator, and a second switching state, in which the additional capacitor (Cadd) is disconnected from the resonator, wherein a capacitance of the resonator is variable dependent on the switching state of the resonator.

2. The ACF converter (600; 610; 700; 710; 720; 900) of claim 1, wherein the ACF converter is configured to be operated at any of at least a first output voltage and a second output voltage, and the resonator is configured to be switched in accordance with the output voltage.

3. The ACF converter (600; 610; 700; 710; 720; 900) of claim 1 or 2, wherein the additional capacitor (Cadd) is configured to produce the capacitance of the resonator in combination with the tank capacitor (Cclamp; Cout), when the resonator is in the first switching state.

4. The ACF converter (600; 700; 710; 900) of any of the preceding claims, wherein the additional capacitor (Cadd) is connected parallel to the tank capacitor (Cclamp; Cout).

5. The ACF converter (610; 720) of any of the preceding claims, wherein the additional capacitor (Cadd) is connected in series to the tank capacitor (Cclamp; Cout).

6. An active clamp flyback, ACF, converter (300; 500; 800) comprising:
   - a switchable clamp circuit (Lk, S2, Cclamp; Lk,p, S2, Cclamp) arranged on an input side of the ACF converter, and
   - a tank capacitor (Cclamp_var; Cout_var) configured to form, in combination with a leakage inductance (Lk; Lk,p, Lk,s) of the ACF

converter, a resonator, when the clamp circuit is switched on,

wherein the ACF converter is configured to be operated at any of at least a first output voltage and a second output voltage at a same primary peak-to-peak current, and a capacitance of the resonator is variable dependent on the output voltage, wherein the first output voltage and the second output voltage differ by at least a factor of 2, and the capacitance of the resonator varies in accordance with a voltage-dependent capacitance of the tank capacitor (Cclamp_var; Cout_var) such that between any of the output voltages a proportion of half a resonance period of the resonator to a demagnetization time of the ACF converter varies by less than a factor of 1.3.

7. The ACF converter (300; 500; 800) of claim 6, wherein the tank capacitor (Cclamp_var; Cout_var) comprises a ceramic capacitor.

8. The ACF converter (300; 500; 600; 610; 700; 710; 720) of any of the preceding claims, wherein the tank capacitor (Cclamp; Cclamp_var) is arranged in the switchable clamp circuit.

9. The ACF converter (800; 900) of any of claims 1 to 7, wherein the tank capacitor (Cout_var; Cout) is arranged on an output side of the ACF converter.

10. The ACF converter (900) of claim 9 including an ACF converter of claim 1, wherein the at least one additional capacitor (Cadd) is arranged on the output side of the ACF converter.

11. The ACF converter (300; 600; 610; 800; 900) of any of the preceding claims, wherein the switchable clamp circuit comprises a high-side clamp.

12. The ACF converter (500; 700; 710; 720) of any of the preceding claims, wherein the switchable clamp circuit comprises a low-side clamp.

13. The ACF converter (300; 500; 600; 610; 700; 710; 720; 800; 900) of any of the preceding claims, wherein the capacitance of the resonator is variable dependent on the output voltage such that at any of the output voltages half of the resonance period is within the range 0.5 to 1.5 times the demagnetization time of the ACF converter.

14. An ACF converter control system (1000) comprising an ACF converter (1020) of claim 1 and a control unit (1010) connected to the ACF converter, wherein the control unit is configured to:

- determine an output voltage of the ACF converter;
- determine, based on the output voltage, a designated switching state of the resonator of the ACF converter;
- generate a switching signal for the resonator in accordance with the designated switching state, and
- output the switching signal towards the ACF converter.

15. A method (1100) of operating an active clamp flyback, ACF, converter, wherein the ACF converter comprises:
    - a switchable clamp circuit arranged on an input side of the ACF converter;
    - a tank capacitor configured to form, in combination with a leakage inductance of the ACF converter, a resonator, when the clamp circuit is switched on, and
    - at least one additional capacitor, wherein the resonator is switchable between a first switching state, in which the additional capacitor is connected to the resonator, and a second switching state, in which the additional capacitor is disconnected from the resonator, wherein a capacitance of the resonator is variable dependent on the switching state of the resonator,

    the method comprising:
    - determining (1110) an output voltage of the ACF converter;
    - determining (1120), based on the output voltage, a designated switching state of the resonator of the ACF converter;
    - generating (1130) a switching signal for the resonator in accordance with the designated switching state, and

    outputting (1140) the switching signal towards the ACF converter.

* * * * *

Fig. 1

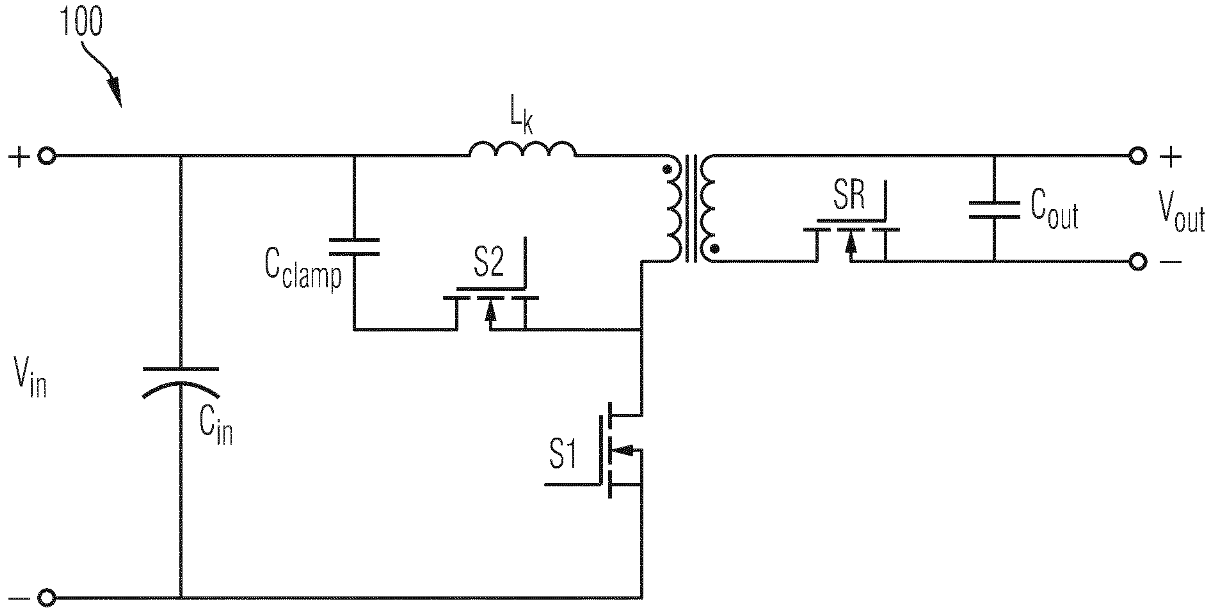

100
L_k
+
−
C_{clamp}
S2
V_{in}
C_{in}
S1
SR
C_{out}
+
V_{out}
−

Fig. 2A

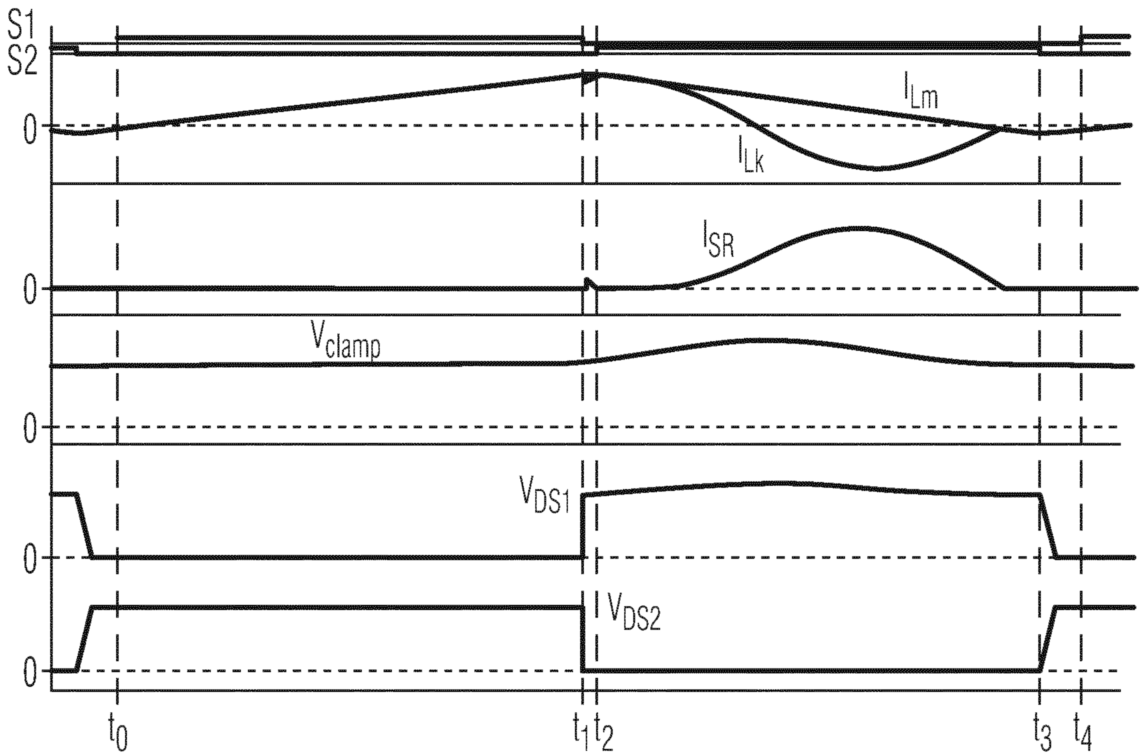

S1
S2
0
I_{Lm}
I_{Lk}
I_{SR}
0
V_{clamp}
0
V_{DS1}
0
V_{DS2}
0
t_0
t_1 t_2
t_3
t_4

Fig. 2B

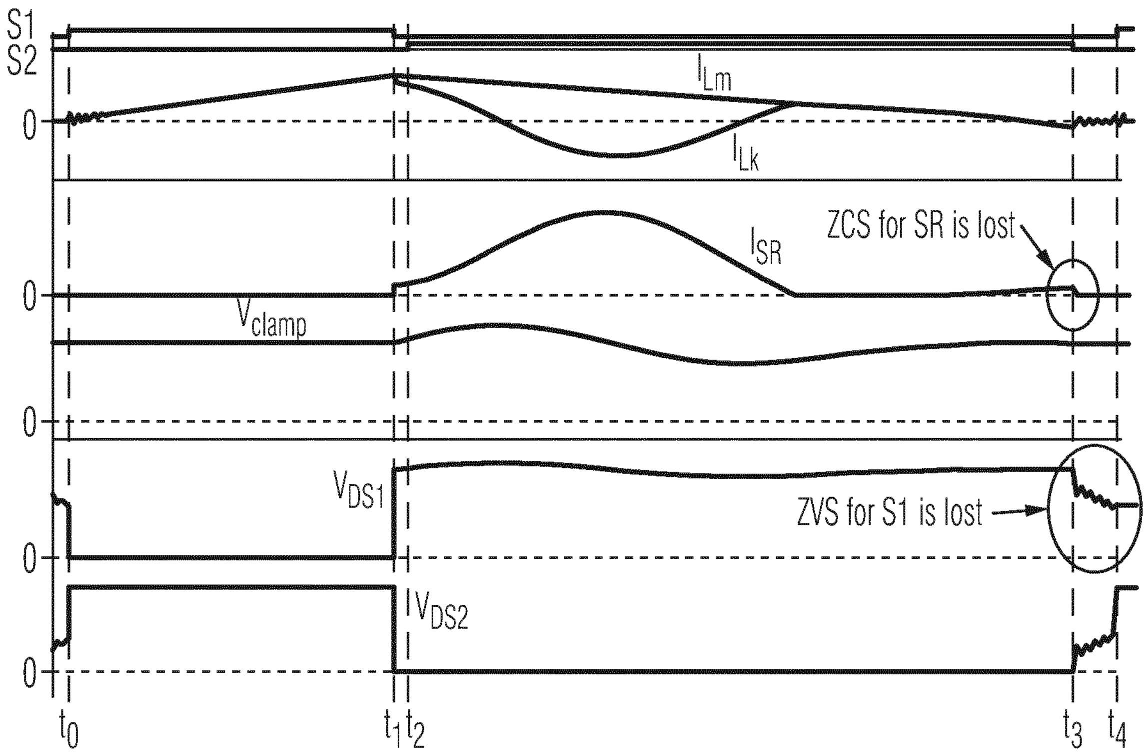
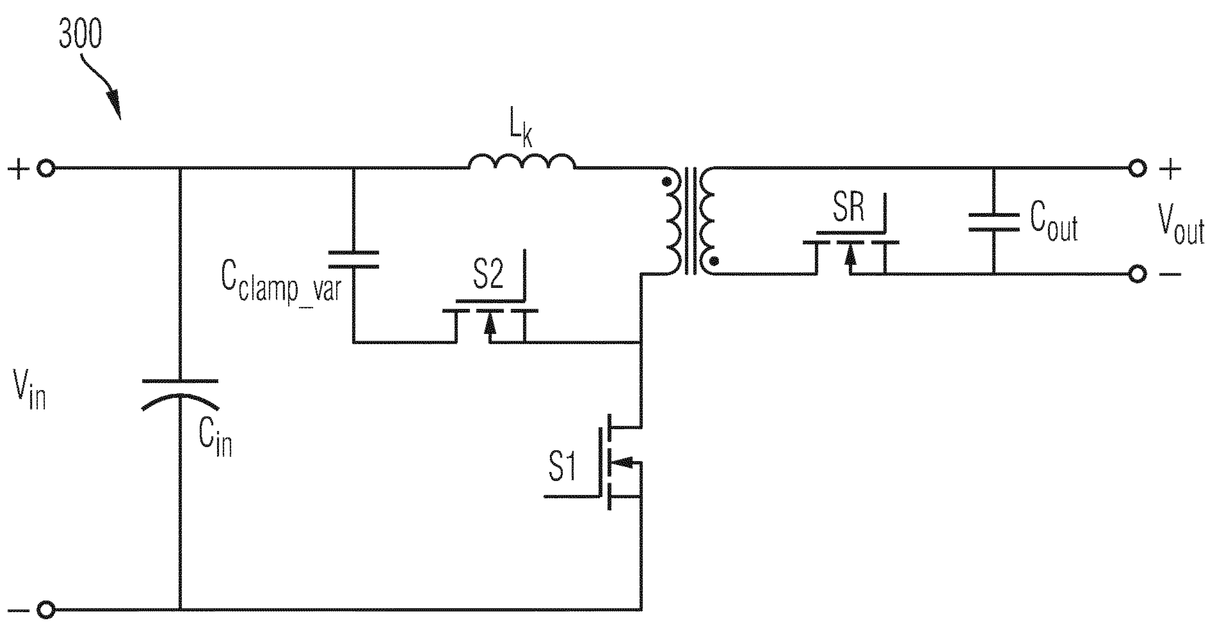

S1
S2
ILm
0
ILk
ZCS for SR is lost
ISR
0
Vclamp
0
VDS1
ZVS for S1 is lost
0
VDS2
0
t0
t1
t2
t3
t4

Fig. 3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Lk
+
Vout
Cout
SR
Cclamp_var
S2
Vin
Cin
S1
−

Fig. 4

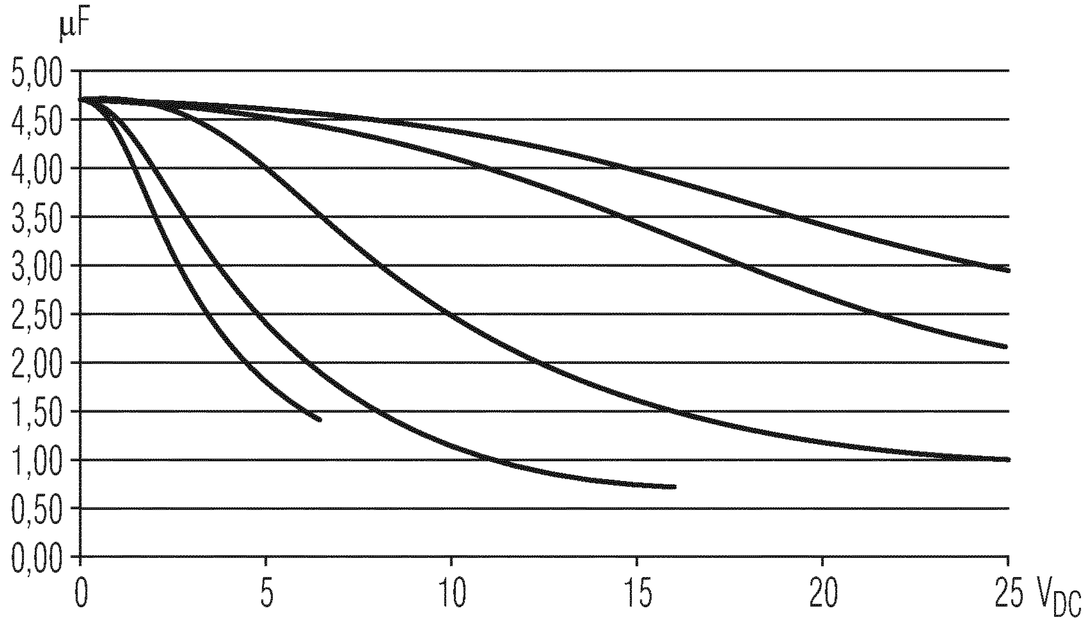

µF
5,00
4,50
4,00
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
0
5
10
15
20
25
V_{DC}

Fig. 5

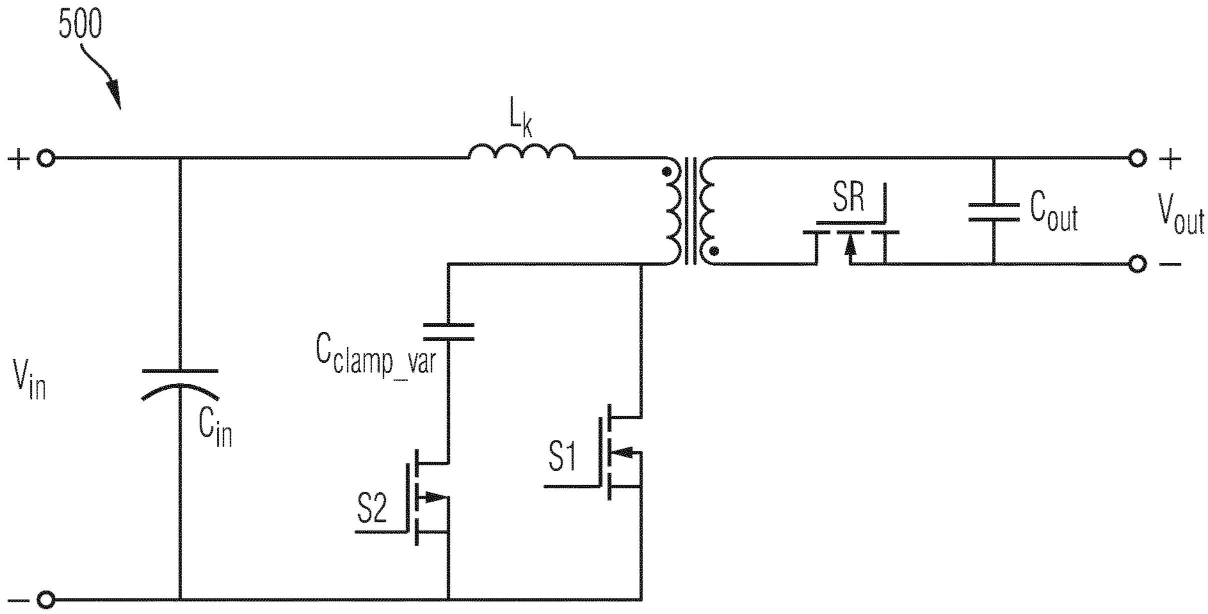

500
L_k
SR
C_out
V_out
V_in
C_in
C_clamp_var
S1
S2
+
−

Fig. 6A

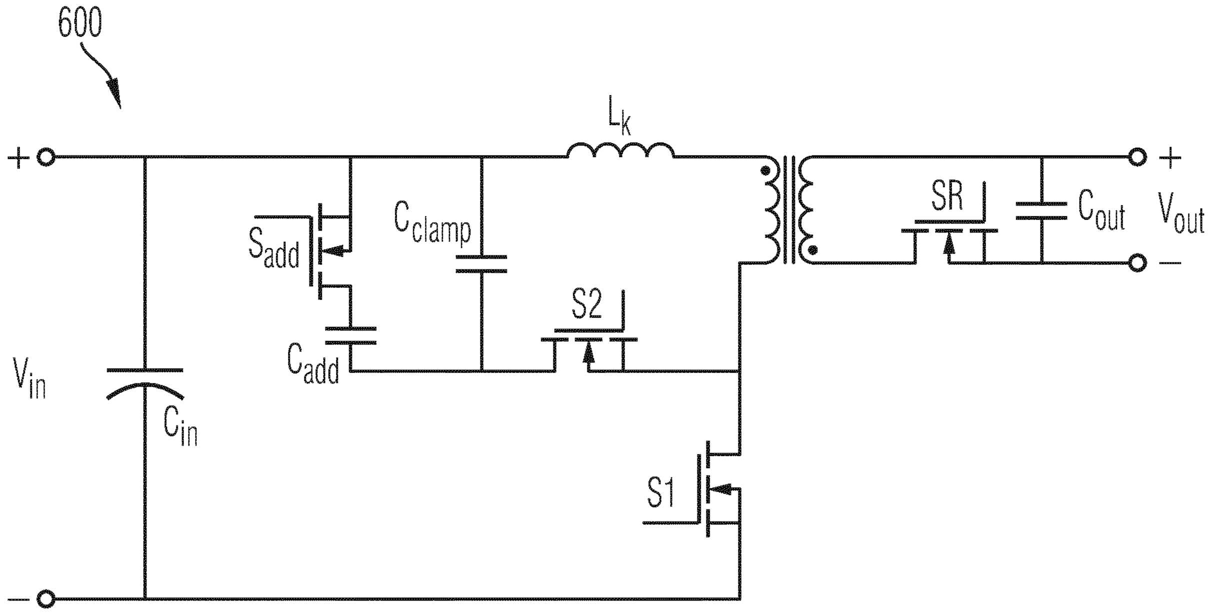

600
Lk
+
−
Vin
Cin
Sadd
Cadd
Cclamp
S2
S1
SR
Cout
Vout
+
−

Fig. 6B

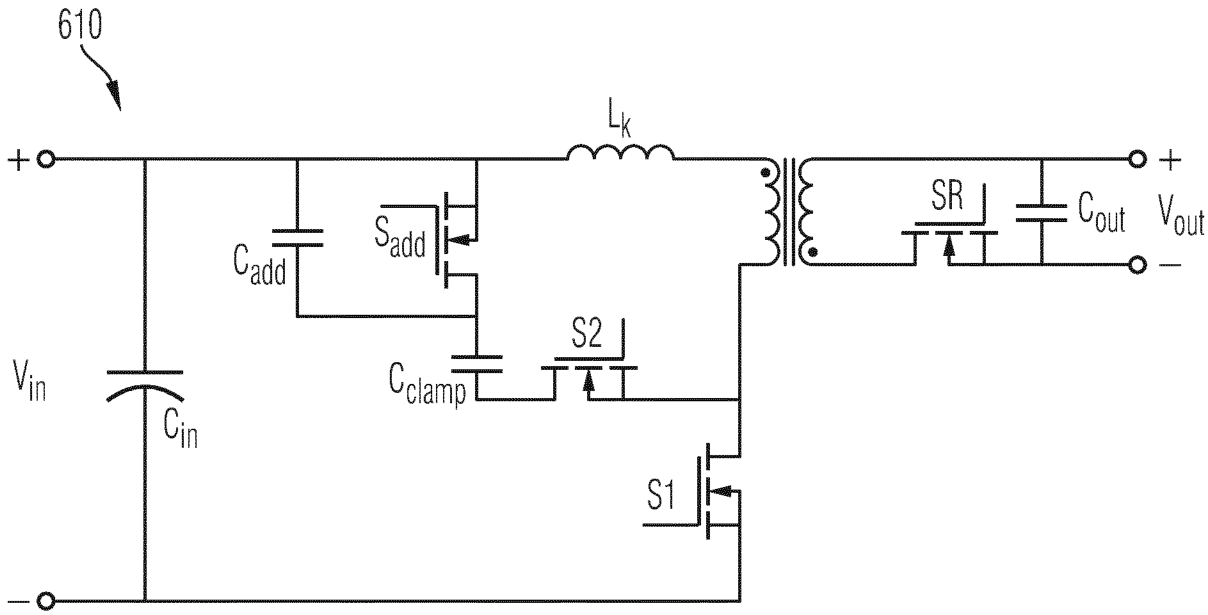

610
Lk
+
−
Vin
Cin
Cadd
Sadd
Cclamp
S2
S1
SR
Cout
Vout
+
−

Fig. 7A

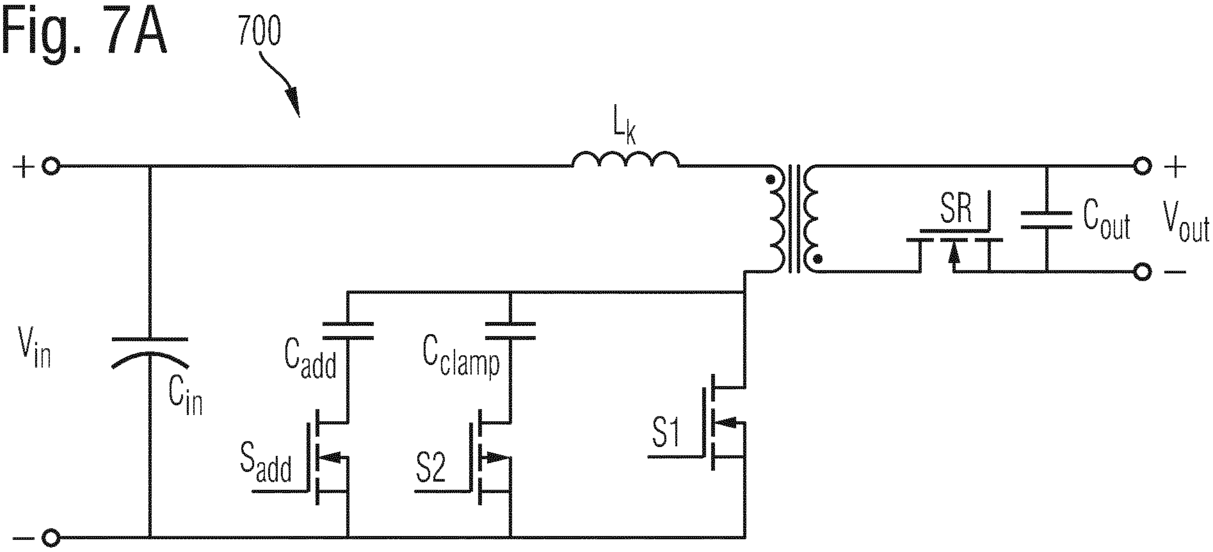


Fig. 7B

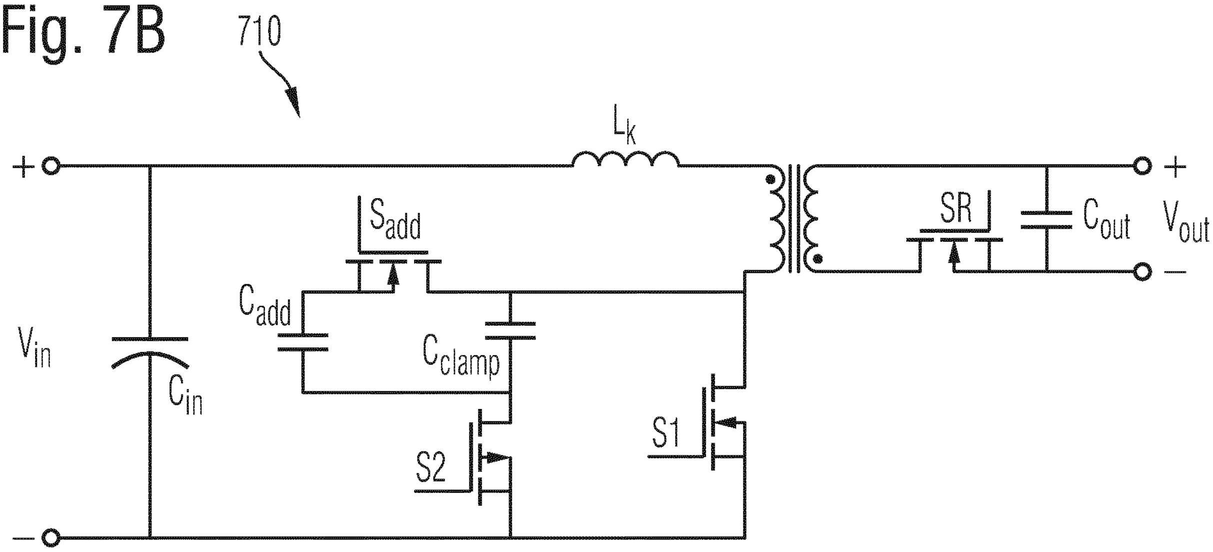


Fig. 7C

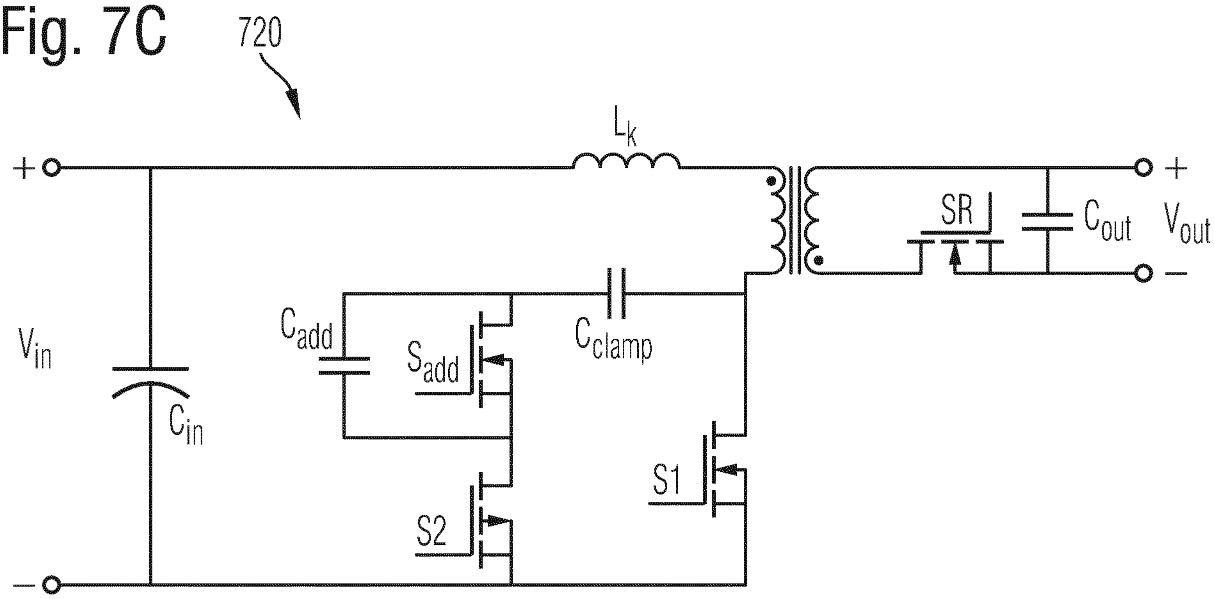


Fig. 8

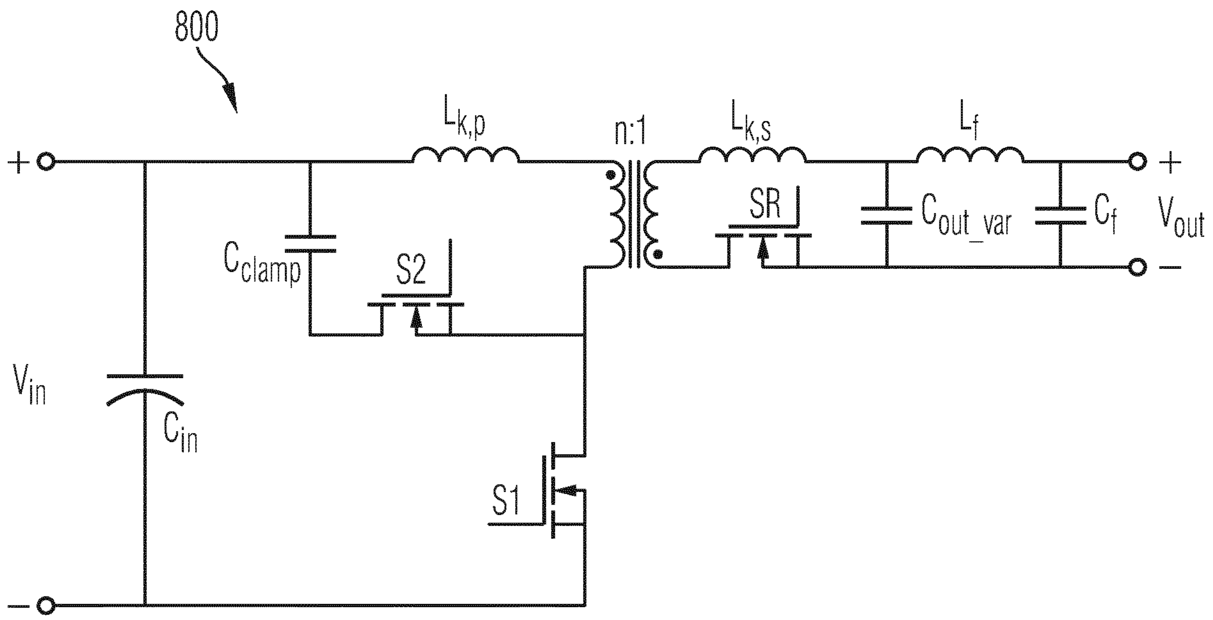

800
$L_{k,p}$
n:1
$L_{k,s}$
L_f
+
C_{clamp}
S2
SR
C_{out_var}
C_f
V_{out}
+
−
V_{in}
C_{in}
S1
−

Fig. 9

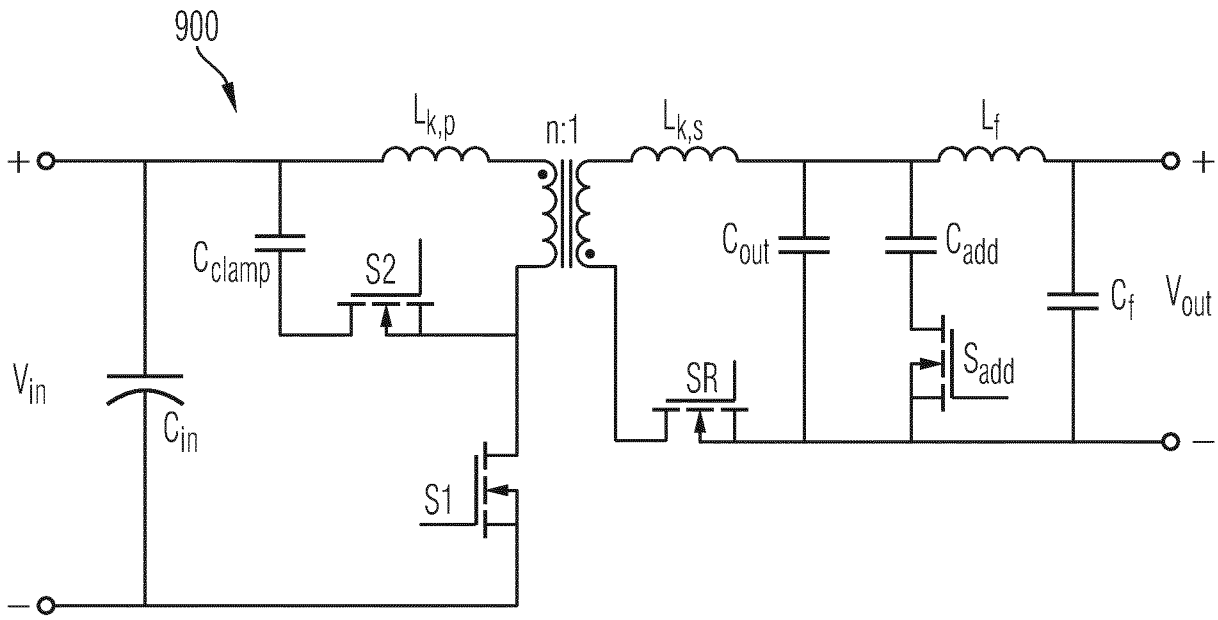

900
$L_{k,p}$
n:1
$L_{k,s}$
L_f
+
C_{clamp}
S2
C_{out}
C_{add}
C_f
V_{out}
+
V_{in}
C_{in}
SR
S_{add}
−
S1
−

Fig. 10

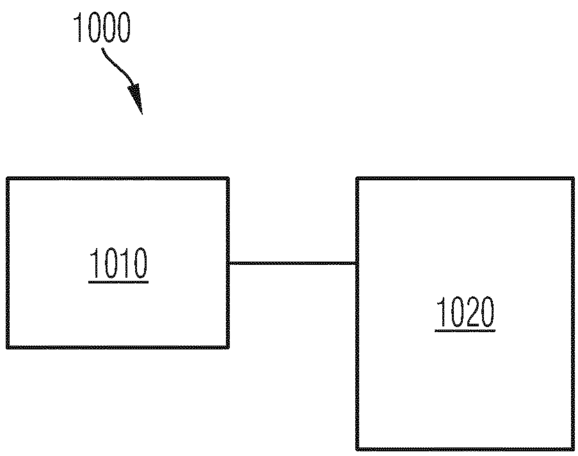
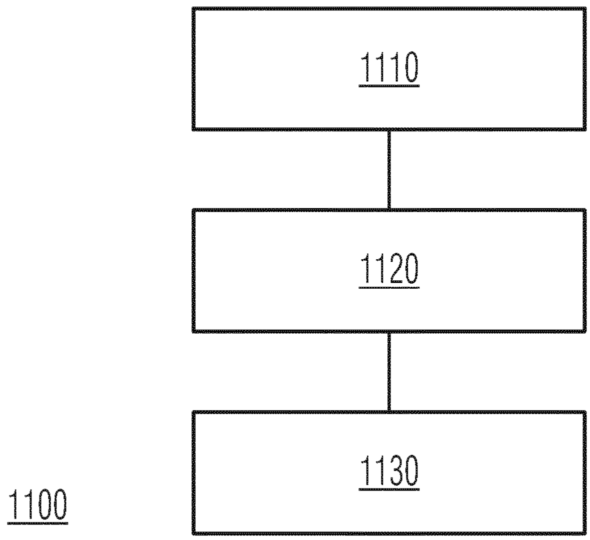


Fig. 11



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/070061

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/08 H02M3/335
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

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 3 107 199 A1 (APPLE INC [US]) 21 December 2016 (2016-12-21)	1,4,5,7, 8,11,12, 14,15
A	figures 1-4	6,13
X	EP 1 182 769 A2 (SONY CORP [JP]) 27 February 2002 (2002-02-27)	1-5, 7-10,14, 15
A	paragraph [0096]; figure 1	6,11-13
A	EP 0 851 566 A2 (PHILIPS ELECTRONICS NV [NL]) 1 July 1998 (1998-07-01) figures 1A, 1B	11,12

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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
7 October 2019	14/10/2019

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	Loiseau, Ludovic

3

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/070061

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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			US	2018083546	A1	22-03-2018
			US	2019222127	A1	18-07-2019
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			TW	529233	B	21-04-2003
			US	2002044469	A1	18-04-2002
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			DE	69719945	T2	22-01-2004
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