Research Article

Improving the One-Step Flyback Microinverter Efficiency for Grid-Connected Solar Panel Using the Soft-Switching Method

Omid Ali Shojaei [a]
Company: SETAREH YAZD Wire & Cable
[a] Master of Electrical, Electronics, Yazd Branch of Azad University, Yazd, Iran.

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Abstract: With the development of industry across the world, the use of energy resources has widely increased. Solar energy has received more attention than other types of energy. Solar energy converters, the most common of which are microinverters, have two functions. First, the converter must track the maximum power operating point of the solar cell and place the solar cell at a maximum operating point. Second, it converts low-voltage DC to AC of the same voltage as the grid and inject a sinusoidal current into the grid. Today, numerous researches has been performed on microinverters, both in terms of control methods and of topology. The most important microinverters include flyback microinverters. In this article, different types of flyback microinverters were examined. Then, to remove the current problems, a new flyback inverter converter was introduced. The proposed inverter had an auxiliary circuit. The auxiliary circuit was simple and had only one auxiliary switch. The auxiliary circuit provides smooth switching conditions for the converter. The flyback converter switch and the auxiliary switch both turn on and off at zero current. Therefore, the converter efficiency increases as the switch stress and switching losses decrease. In this article, this inverter was fully investigated. Also, it was discussed how auxiliary circuit elements were designed and their converter switches were explained, and then a theoretical analysis of converters was confirmed using simulation findings.

Keywords: Flyback Inverter, Soft Switching, ZVT Zero Voltage Switching, ZCT Zero Current Switching

1. Introduction

Today, renewable energy sources are widely used across the globe as the world population has grown, energy resources are limited and the indiscriminate consumption of fossil fuels has caused adverse effects on the environment. One of the renewable sources is solar energy, which is focused attention because of its myriad advantages. Because of great potentialities and benefits, solar energy is increasingly used in industrialized countries. Iran is located between 25 to 40° north latitude in a region where sun energy is abundant. The amount of solar radiation in Iran is estimated between 1800 to 2200 kwh/m2 per year, which is higher than the world average. In Iran, on average, over 280 sunny days are reported annually, which is very substantial. Despite the existence of a suitable climate in Iran for using solar energy, the use and efficiency of this type of clean energy has been very weak.

Methods of using solar energy are generally divided into three categories:
A. Solar-thermal systems
B- Solar thermal-electric systems
C. Photovoltaic systems

Originally developed for space applications, PV photovoltaic systems convert light energy into electrical energy directly. The basic presumption underlying this technology is the "photoelectric" phenomenon first proposed by Einstein. Photovoltaic cells, or solar cells are crystals made of thin layers of semiconductors (silicon and arsenic gallium). As the sun radiation and temperature change, the voltage current curve of the solar cell changes also. As the radiation increases, short-circuit current curve of the solar cell increases; therefore, as the shadow falls on the panel, the cell power decreases, and also, as the temperature increases, the open circuit voltage of the solar cell decreases. One way to use solar energy it to apply it in solar panels. The electricity generated by low-voltage DC power solar panels is low. This electricity must be converted to an appropriate AC voltage and then transmitted to the grid. There are various ways to connect a solar panel to the grid. One of the newly used methods is to use microinverters. Micro inverters connect the solar panel power to the grid directly. This method has such advantages as high efficiency and high reliability. There are various types of micro inverters and they can be applied as needed. The voltage generated by a solar cell is about half a volt. This voltage is very insignificant. Therefore, solar cells are arranged in series to increase the overall voltage. It is also possible to parallel several strings together to increase its current output. The set of solar cells arranged alongside each other form a solar panel or module. The electricity generated by the solar panel is low-voltage DC power (about 65 volts). Therefore, the electricity generated by the solar panels cannot be directly connected to the grid, and this must be done by electronic power converters. The DC voltage of the solar panel is converted to a higher-level DC voltage using electronic power converters, finally being converted by an inverter into the AC power with a grid-proportional frequency and amplitude. There are different techniques for connecting solar cells, the most important of which are: using a central inverter, string inverter and microinverter. In microinverters, DC to AC energy conversion and maximum power tracking of a solar panel are simultaneously performed, and therefore these converters will yield higher efficiency and more reliability as they are widely used in industry.

One of the simplest structures in inverters is the flyback microinverter. In this microinverter, the solar panel-generated power is converted to AC power in one step and thus connected to the grid. To have better efficiency, it is necessary to remove audible noise, to make it easier to remove harmonics and to reduce the size of the output filter to increase the switching frequency of the microinverter. The switching frequency of the flyback inverter is restricted because of the following:

1) Switching stress (high voltage peak on the switch when turned off),
2) Switching losses
3) Intense di/dt and dv/dt, causing electromagnetic interference (EMI).

First, snubber was used in the flyback inverter to remove the switching losses. Although di/dt and dv/dt snubbers reduce switches when turned on and off, thus reducing the EMI, they simply remove the switching losses from the power switch while not reducing the total converter losses; hence, they are widely used as protecting the power switch. In order to remove these three problems, the idea of soft-switching in the flyback inverter was suggested. In soft switching techniques, a high frequency resonant circuit is added to the flyback inverter circuit. The resonant circuit includes L and C elements along with extra elements such as switches and diodes. Therefore, the voltage and current oscillate and pass through the zero point, thus providing a soft switching condition for the flyback inverter switch. The switch waveform is made by the resonant circuit in order to minimize the switch loss, to reduce its stress, and to prevent EMI, thus improving the circuit efficiency. In this paper, various types of converters for grid-connected solar panels were examined, with the function of each explained. Each of these converters has advantages and disadvantages. In order to solve the problems and eliminate the disadvantages of the existing converters, an inverter flyover converter with a new soft switching function was provided. The performance of this inverter is fully examined. This inverter has an auxiliary circuit. This converter has one main switch, one auxiliary switch and two low frequency switches. Then the theoretical analysis of the converter was confirmed by simulating PSIM software.

A microinverter-based solar power system is very expensive. However, the system has a higher efficiency and is more reliable. In a micro-inverter, the low-voltage solar panel-generated power is converted to AC power. Energy conversion is done in different processes. Therefore, there are various micro inverters such as non-isolated, isolated, single-phase, multi-phase, single-directional and bi-directional microinverters. Inverters with isolated transformers are more applicable on protection grounds. Single-phase inverters have a simpler structure than multi-phase inverters, and because the conversion process is performed in one phase, they enjoy a higher efficiency. In these inverters, an auxiliary circuit is added to the main flyback inverter. The auxiliary circuit provides soft switching conditions for the main inverter switch. Each of the inverters under study has advantages and disadvantages. Flyback inverters with active clamp circuit have a simpler structure compared to other inverters.

2. Materials and Methods

The flyback microinverter of the proposed soft-switching with a ZCT circuit is illustrated in Fig. 1. This inverter is made of a conventional flyback inverter and an auxiliary circuit. The auxiliary circuit of this inverter consists of an auxiliary switch, a resonant capacitor, two resonant inductors and a diode. The auxiliary circuit sets the ground for the soft switching for the main switch of the flyback converter at any desired time. The inverter proposed functions with different modulation methods in flyback micro-inverter converters such as DCM and BCM. The following is how this micro inverter operates. Fig. 1 illustrates the switch waveforms of the circuit, such as auxiliary switch gate commands, capacitor voltages, inductor currents, and main auxiliary switch currents. Inverter operation has 9 modes. These situations are as follows

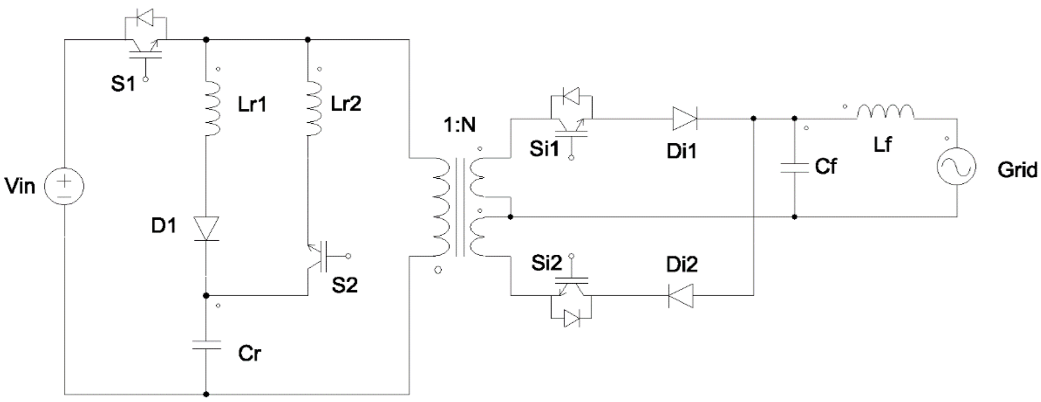


Fig. 1. The proposed ZCT flyback microinverter.

Because the switching frequency of the converter is much greater than the grid frequency, such parameters as grid current, grid voltage, load coefficient and reference current are almost constant in a switching period. To analyze the circuit performance, it is assumed that LL1 is the transformer leakage inductor and Lm is the transformer magnetizing inductor. Also, the ratio of transformer velocity is 1: N. Prior to the first mode, it is assumed that the voltage Cr is equal to V0, the resonant inductor currents equal zero, and all switches except the Si1 switch are off.

2.1. Process of designing inverter elements

The elements to be designed in this microinverter are the main and auxiliary switches, the ratio of the transformer velocity, the level of transformer magnetizing inductor, and the resonance elements including the inductor Lr1, the inductor Lr2 and the capacitor Cr. The voltage stress of switch S1 is equal to:

$$V_{S1} = V_{in} + V_o \frac{1}{N} \tag{1}$$

In this equation, Vin equals the input voltage, V0 the output voltage, and N the ratio of the transformer velocity. Having the maximum value of the output voltage, the voltage stress of switch S1 can be calculated. To provide soft switching conditions for inverter switches, the converter must operate in a DCM or BCM mode. Assuming the converter operating in DCM mode, the voltage balance equation for the transformer is:

$$V_{in} T_{on} = V_o \frac{1}{N} T_r \tag{2}$$

In this equation, Ton is the time when the transformer magnetizing inductor is charged and Tr is the time it takes for the transformer magnetizing inductor energy to be transmitted to the grid. Given that the converter operates in a DCM mode, we have:

$$T_{on} + T_r + T_d = T \tag{3}$$

In this equation, Td is the time of mode nine and the T is the switching period. Given that the converter operates in a DCM mode, if an additional 20% design is considered, we have:

$$T_d = 0.2T \tag{4}$$

In this case, the Ton equation is equal to:

$$T_{on} = \frac{V_o \frac{1}{N} 0.8T}{V_{in} + V_o \frac{1}{N}} \tag{5}$$

As Ton, Tr, and D are determined, to calculate magnetizing inductor we have:

$$P = \frac{1}{2} L_m I_P^2 f \tag{6}$$

Where Lm is the transformer magnetizing inductor, f is the switching frequency and P is the output power of the converter. IP is the initial current of the transformer being equal to:

$$I_P = \frac{V_{in} T_{on}}{L_m} \tag{7}$$

Therefore, the transformer magnetizing inductor equation is equal to:

$$L_m = \frac{V_{in}^2 D^2}{2Pf} \tag{8}$$

The Lr1 inductor provides ZCS conditions for the S1 switch when it is on and is designed as follows based on a turning-on snubber [1-3].

$$Lr1 > \frac{V_{sw} t_r}{I_{sw}} \tag{9}$$

In the above equation, Isw is the switch current after switching on, Vsw is the switch voltage before switching on, and tr is the time it takes for the switch current to reach a final value after switching on. The voltage equation of switch S2 is equal to:

$$V_{S2} = V_{Cr} - V_{in} \tag{10}$$

According to the Vcr equation, this capacitor is approximately charged twice the input voltage. Therefore, the voltage stress of switch S2 is equal to:

$$V_{S2\_\max} = V_{in} \tag{11}$$

Cr is so selected that the resonance time of mode two is approximately 15% of the switching period. In this case we have:

$$T_{resonance} = 0.2T = \pi\sqrt{L_{r1}C_r}$$

$$C_r = (\frac{0.2T}{\pi})^2 \frac{1}{L_{r1}} \tag{12}$$

The capacitor Vcr is charged almost twice the input voltage. Therefore, the value of the inductor Lr2 is selected such that it will be greater than the peak current of switch S1 during resonance along with the capacitor Cr, and the peak current of the inductor Lr2, and the reverse parallel diode of switch S1 is switched on in order that switch S1 can change under soft switching conditions. Therefore, with 20% extra design we have:

$$V_{in} \frac{\sqrt{C_r}}{\sqrt{L_{r2}}} = 1.2 I_{S1\max} \tag{13}$$

$I_{S1\max}$ is the maximum current of switch S1 being equal to the maximum initial current of the transformer.

$$I_{S1\max} = I_p \tag{14}$$

Therefore, the value of the inductor Lr2 is selected as follows:

$$L_{r2} = (\frac{V_{in}\sqrt{C_r}}{1.2 I_P})^2 \tag{15}$$

The voltage stress of the secondary switches Si1 and Si2 is equal to twice the output voltage because of the presence of a transformer and that one of the switches is switched on in each stage equals the output voltage.

$$V_{Si1\max} = V_{Si2\max} = 2V_{o\max} \tag{16}$$

The voltage stress of the secondary diodes Di1 and Di2 is also calculated as follows:

$$V_{Di1\max} = V_{Di2\max} = V_{in}N + V_{o\max} \tag{17}$$

2.2. Designing control circuit

The suggested converter of the flyover inverter consists of one main high frequency switch S1, one high frequency switch S2 and two low frequency switches in the secondary Si1 and Si2. Secondary switches are switched based on the output voltage. If the output voltage is found to be positive in the half cycle, switch Si1 is turned on and switch Si2 is off. If the output voltage is found to be negative in the half cycle, switch Si2 is turned on and switch Si1 is off.

The general schematic of the control circuit is illustrated in Fig. 2. In the control circuit, a PI controller has been used to reduce the error between the output voltage and the reference voltage. In order to generate PWM pulses, the PI controller output is compared with a wave of high-frequency saw teeth, and finally a PWM pulse is made. As the figure shows, the PWM pulse is applied to switch S1 with a delay. The value of this delay is calculated based on the half-resonance time between the inductor Lr2 and the capacitor Cr. Thus, we have:

$$D_1 = \frac{1}{2}\pi\sqrt{L_{r2}C_r} \tag{18}$$

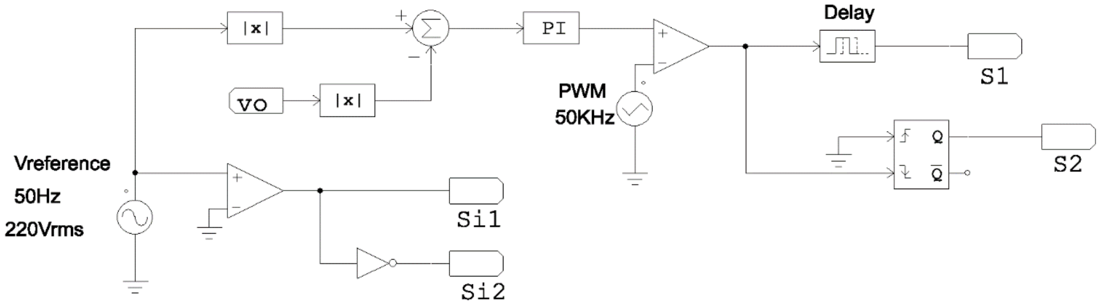


Fig. 2. Converter switch control circuit.

The switch S2 current turns zero after the resonance ends, so we turn off this switch after the current becomes zero. The time at which switch S2 is on is equal to the sum of three, four, five and six modes.

3. Results and Discussion

3.1. Simulation results

To demonstrate the true inverter performance, the proposed inverter simulation was performed by PSIM software. In this simulation, the voltage of the solar panel is assumed to equal to 65V DC. The output voltage of the gird is also assumed to be 220Vrms with a frequency of 50 Hz. The microinverter power is 100 watts and the switching frequency is 65 kHz. According to the input voltage of 220 Vrms, the peak voltage of switch S1 is equal to:

$$V_{S1\_\max} = \frac{V_o}{N} + V_{in} = \frac{311}{N} + 65$$

If we consider the peak voltage of switch S1 as 200 V, we have:

$$200 = \frac{V_o}{N} + V_{in} = \frac{311}{N} + 65$$

$$N = 2.3 \cong 3$$

By calculating the ratio of transformer velocity, the voltage peak of switch S1 is equal to:

$$V_{S1\_\max} = \frac{V_o}{N} + V_{in} = \frac{311}{3} + 65 = 169V$$

To calculate the transformer leakage inductor, we have based on Equation (17):

$$T_{on} = \frac{V_o \frac{1}{N} 0.8T}{V_{in} + V_o \frac{1}{N}} = \frac{311 \times \frac{1}{3} \times 0.8 \times \frac{1}{65000}}{65 + 311 \times \frac{1}{3}} = 7.5us$$

As Ton is determined, D is equal to:

$$D = \frac{T_{on}}{T} = 7.5u \times 65000 = 0.487$$

To calculate the magnetizing inductor, based on the transformer inductive equation, we have:

$$L_m = \frac{V_{in}^2 D^2}{2Pf} = \frac{65^2 \times 0.487^2}{2 \times 100 \times 65000} = 75uH$$

The inductor Lr1 is an switching-on snubber, designed in accordance with $20uH$.

The maximum value of the capacitor Cr according to the following equation is equal to:

$$C_{r\_\max} = (\frac{0.2T}{\pi})^2 \frac{1}{L_{r1}} = (\frac{0.2}{\pi \times 65000})^2 \frac{1}{20u} = 48nF$$

The capacitor Cr is considered equal to $30nF$. The maximum current of switch S1 is equal to:

$$I_P = I_{S1\_\max} = \frac{V_{in} T_{on}}{L_m} = \frac{65 \times 7.5u}{75u} = 6.5$$

The minimum value of the inductor Lr2 is equal to:

$$L_{r2\_\min} = (\frac{V_{in}\sqrt{C_r}}{1.2 I_P})^2 = (\frac{65 \times \sqrt{30 \times 10^{-9}}}{1.2 \times 6.5})^2 = 2uH$$

In order to better demonstrate the soft switching conditions for switch S1, the inductor value Lr2 is selected equal to $1.5uH$. All circuit elements in the simulation are summarized in Table 1.

Table 1. Simulation elements.

Parameter	Value
Cr	30nF
Lr1	20uH
Lr2	1.5uH
N	3
Lm	75uH
VS1max	170
VS2max	65
Vo	220 V- 50Hz
Vin	65 VDC
P	100 w
fsw	65kHz

The converter of the flyback inverter simulation is performed in PSIM 9 software. The general schematic of the simulation is illustrated in Fig. 3. The waveforms of voltages and pulses of the switch gates are displayed in Fig. 4. As shown in this figure, switch S2 turns on before switch S1 turns on and turns off after switch S1 turns off. This figure also shows the situation where the switch Si1 is on and the switch Si2 is off with the power transmitted to the grid via the switch Si1. In the voltage wave, the switch S1 is on in ZCS mode and off in ZCS mode. In the switch S2 it is on and off in ZCS mode. In the switch Si1, the voltage is zero when the switch turns on. Because there is no overlap between the voltage and current of the switch, its switching losses are insignificant. In the auxiliary diode D1, it is clear that this diode turns on and off in ZCS mode. Also, the voltage stress of this diode is approximately equal to the input voltage. In the main diode Di1, the voltage stress of this diode is about 500 volts. In the capacitor voltage Cr and inductor current Lr1, it is clear that the capacitor Cr is charged up to approximately 130 volts. In the current waveform, the switch Si1of the converter operates in a DCM mode. In secondary switch currents with inverter output current, it is clear that the switch Si1 is on when the output current is positive at peak, and the switch Si2 turns on when the output current is negative at half-cycle.

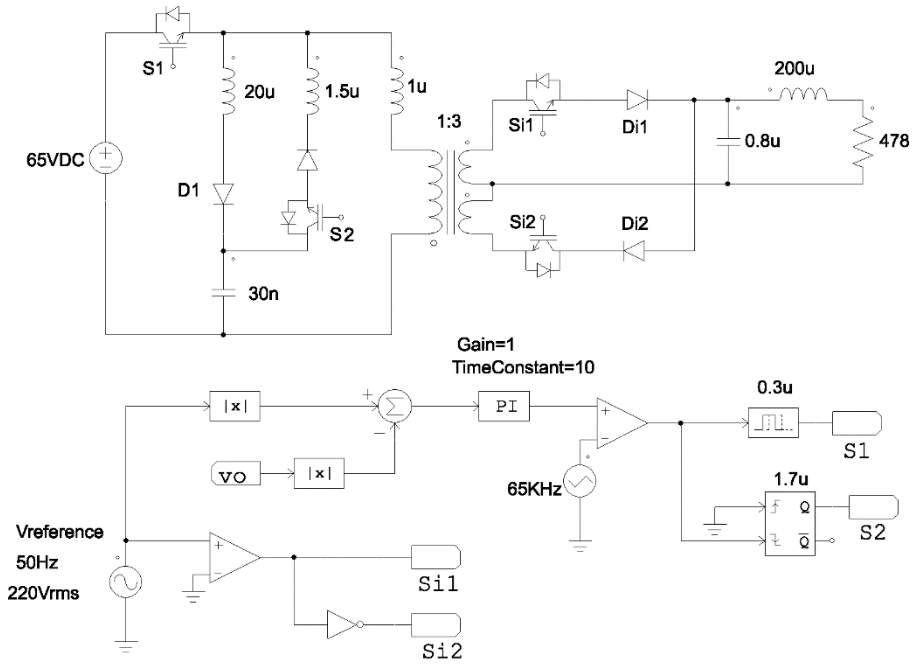
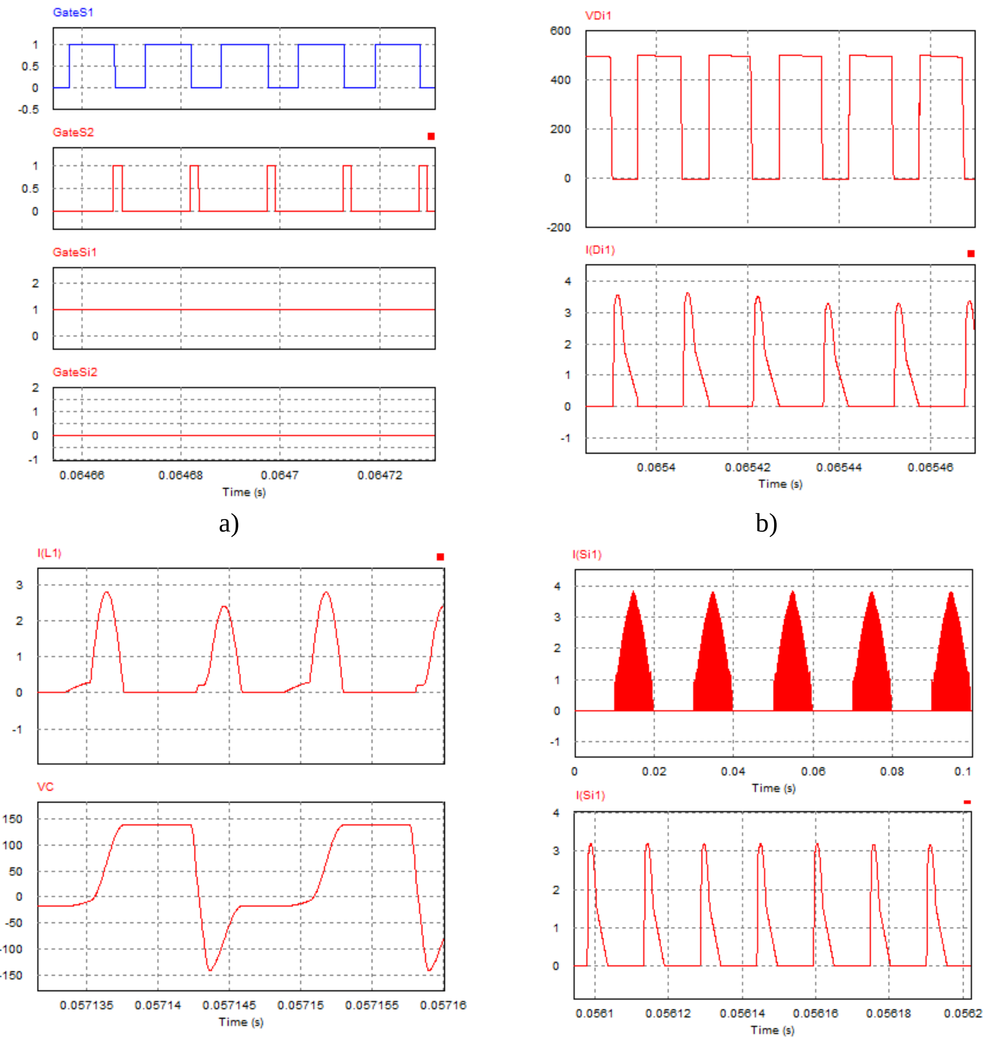
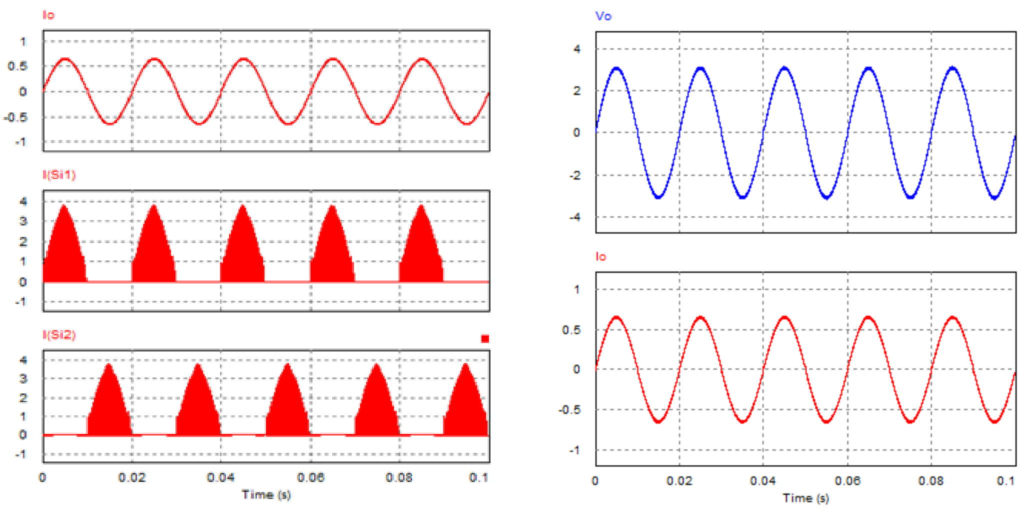


Fig. 3. General schematic of converter simulation in PSIM software.



a) b)

c) d)



e) f)

Fig. 4. a) Waveform pulses of switch gates, b) Voltage and current waveform of main diode Di1, c) Current waveform Lr1 and voltage Cr, d) Current waveform of switch Si1 above and its zoomed state at the bottom, e) Output current waveform at the top, Si1 current in the middle and Si2 current at the bottom, f) Output voltage waveform at the top and output current at the bottom.

3.2. Selection of switches and diodes

If, as the simulations suggests, the circuit parameters have 65V input voltage, 220V output voltage with 50Hz frequency, 100W output power, and transformer velocity ratio of 3, then the voltage and current stress of the main switch S1 is equal to:

$$V_{S1\_\max} = \frac{V_o}{N} + V_{in} = \frac{311}{3} + 65 = 169V$$

$$I_{S1\max} = \frac{V_{in} T_{on}}{L_m} = \frac{65 \times 7.5u}{75u} = 6.5A$$

Therefore, IRFP240 MOSFET is used for S1 [4]. This switch has a voltage of 200 volts, a current of 20 amps and a conductivity of 0.18 ohms. The voltage and current stress of switch S2 is equal to:

$$V_{S2\_\max} = V_{in} = 65V$$

$$I_{S2\max} = V_{in} \frac{\sqrt{C_r}}{\sqrt{L_{r2}}} = 65 \times \frac{\sqrt{30n}}{\sqrt{1.5u}} = 9.2 \cong 10A$$

Therefore, like S1, IRFP240 MOSFET can be used for S2. The voltage and current stress of the secondary switches Si1 and Si2 is equal to:

$$V_{Si1\max} = V_{Si2\max} = 2V_{o\max} = 2 \times 220\sqrt{2} = 622V$$

$$I_{Si1\max} = I_{Si2\max} = \frac{I_p}{N} = \frac{10}{3} = 3.3.A$$

Therefore, MOSFET IXFL44N100P-ND can be used for Si1 and Si2 [5]. This switch has a high voltage switch with low conductivity resistance. This switch has a voltage of 1200 volts, a current of 22 amps and a conductivity of 0.24 ohms. Voltage and current stress of auxiliary diode D1 is equal to:

$$V_{D1\max} = V_{in} = 65V$$

$$I_{Si1\max} = \frac{V_{in}\sqrt{C_r}}{\sqrt{L_{r1}}} = \frac{65 \times \sqrt{30n}}{\sqrt{20u}} = 2.5A$$

MUR440 diode can be used for D1 [6]. This diode has a voltage of 400 volts and a current of 4 amps. The voltage and current stress of the main diodes Di1 and Di2 is equal to:

$$V_{Di1\max} = V_{Di2\max} = V_{in}N + V_{o\max} = 65 \times 3 + 220\sqrt{2} = 506V$$

Diode FR307 can be used for D1 [7]. This diode has a voltage of 1000 volts and a current of 3 amps.

3.3. Improving the efficiency of flyback microinverter using a four-switch inverter

The converter of the flyback inverter has a simple structure and consists of only one transformer, one switch in the primary, two switches and two diodes in the secondary to the transformer. However, this structure also has some drawbacks. This converter makes use of a three-winding transformer to generate a sine wave current at the output. Therefore, compared to a two-winding transformer, a three-winding transformer includes a larger core and more winding. Therefore, the core-based losses of the transformer and its winding losses are greater compared to the two-winding transformer. The most important drawback of this converter is the voltage stress of the secondary switches. This converter is made of two switches in the secondary. Because a three-winding transformer is used, the voltage stress of each of these two switches is at least twice the output voltage. It should also be stated however that it may be more than twice because of the current oscillations in the output of this voltage. As the tolerable voltage of the switch increases, the conductivity resistance of the switch also increases, resulting in increased conductivity loss of the converter. If two switches are used at the output instead of a three-winding transformer, a conventional transformer and an H inverter with four switches in the secondary can be applied. In this case, the maximum voltage of the switches will be half of the previous mode. As the voltage decreases, a switch of a much lower conductivity resistance can be used, resulting in reduced conductivity losses of the converter. This converter is shown in Fig. 5. The way the auxiliary circuit operates in the primary of the converter transformer with a four-switch inverter is similar to the previous inverter, so it is not expressed again. Here, the three-winding transformer is replaced by a two-winding transformer. The characteristics of this transformer are the same as the previous transformer and both have the same magnetizing inductor.

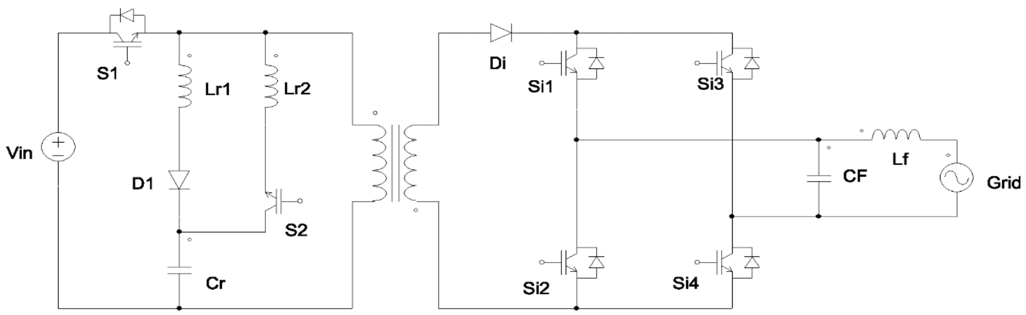
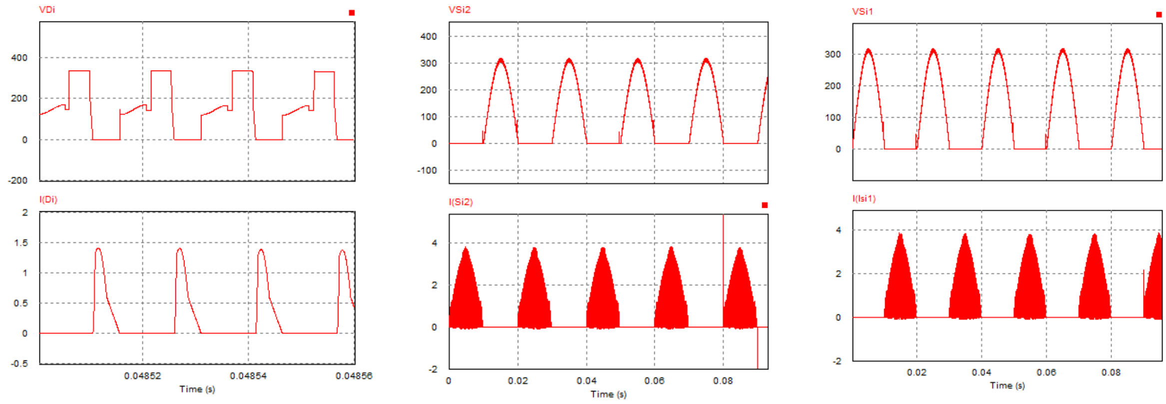


Fig. 5. Flyback microinverter using a four-switch inverter.

As the figure shows, it is clear that diodes Di1 and Di2 are removed and only one diode Di is in the circuit. However, because the current passing through this diode is the sum of diodes Di1 and Di2, the conductivity losses of this diode are equal to the previous two diodes. Also, the voltage at both ends of this diode is equal to the voltage of the previous circuit diodes. As stated, four switches have been used in the secondary of this converter. Switches Si1 and Si4 turn on at the same time simultaneously when the output voltage is in the positive half cycle. Switches Si2 and Si3 also turn on when the output voltage is in the negative half cycle. The voltage stress of these switches is equal to the maximum output voltage of the converter. This converter was also simulated by PSIM 9 software. All the parameters of this simulation look like the previous converter. The voltage and current waveform of the diode Di is shown in Fig. (6a). The voltage and current waveform of the switch Si1 is shown in Fig. (6b). As shown in this figure, the maximum voltage of the two switches is equal to $220\sqrt{2}$ whose value is half that of the previous converter. The waveform of the switch Si4 is also equal to the waveform of the switch Si1. The voltage and current waveform of the switch Si2 is shown in Fig. (6P). The waveform of the switch Si3 is also equal to the waveform of the switch Si2.



a) b) c)

Fig. 6. a) Diode voltage and current waveform Di, b) Si1 switch voltage and current waveform, c) Si2 switch voltage and current waveform.

3.4. Calculating flyback microinverter losses

Switching losses occur as the voltage and switch current overlap at times switches are on and off. These losses increase as converter switching frequency increases. These losses are divided into two parts: losses from switching on and off. Switching-on related losses are calculated based on the following equation [8, 9]:

$$P_{Loss-on} = \frac{1}{2} V_{ds-on} I_{d-on} t_{on} f_{sw} \tag{18}$$

$$P_{Loss-off} = \frac{1}{2} V_{ds-off} I_{d-off} t_{off} f_{sw} \tag{19}$$

In this equation, V_{ds-off} is the switch voltage after it is off, I_{d-off} is the switch current before it is off and t_{off} is the time the witch is off. In a conventional flyback converter, because the energy of the transformer leakage inductor is dissipated at switch S1 or the snubber circuit when the switch is off, these losses account for a significant portion of the total losses of the converter. For this converter we have:

$$P_{Loss-off\,S1} = \frac{1}{2} V_{ds-off} I_{d-off} t_{off} f_{sw} = \frac{1}{2} \times 170 \times 6.5 \times 122 \times 10^{-9} \times 65000 = 4.38 \tag{20}$$

In the proposed converters 1 and 2, the auxiliary circuit is tasked with reducing these losses. Switch S1 turns off under soft switching conditions due to the operation of the auxiliary circuit, with the switching losses from this switch reaching zero. Switch S2 turns off after its current becomes zero. Therefore, this switch is turned off in a ZCS mode and as a result, the switching losses from this switch become zero. Secondary switches turn off in a ZVS mode. Therefore, the losses from these switches will also be zero.

The conductive circuit losses are divided into two parts: conductive losses of the diodes and the conductive losses of the switches. Diode conductive losses are calculated based on the following equation [8,9].

$$P_{cond-loss} = I_{ave-D} \times V_F \tag{21}$$

In this equation, I_{ave-D} is the average current of the diode and VF is the conductive voltage of the diode. These losses are later calculated for all three types of converters.

3.5. Conductive losses of conventional flyback converter diodes

A standard flyback converter has two diodes of Di1 and Di2. If FR307 diode is used for Di1 and Di2, the amount of conductive losses of these diodes equals to:

$$P_{cond-loss\ Di1} = I_{ave-D} \times V_F = 0.206 \times 1.3 = 0.268$$

$$P_{cond-loss\ Di2} = I_{ave-D} \times V_F = 0.206 \times 1.3 = 0.268$$

3.5.1. Conductivity losses of the diodes of the proposed flyback converter 1

The proposed flyback converter 1 has two diodes of Di1 and Di2 in the secondary and one diode D1 in the primary. If MUR440 diode is used for D1 and FR307 diode for Di1 and Di2, the loss value of the circuit diodes is equal to:

$$P_{cond-loss\ \ D1} = I_{ave-D} \times V_F = 0.49 \times 1.05 = 0.515$$

$$P_{cond-loss\ \ Di1} = I_{ave-D} \times V_F = 0.21 \times 1.3 = 0.273$$

$$P_{cond-loss\ \ Di2} = I_{ave-D} \times V_F = 0.21 \times 1.3 = 0.273$$

3.5.2. Conductivity losses of the diodes of the proposed flyback converter 2

The proposed flyback converter 2 has a diode Di1 in the secondary and a diode D1 in the primary. If MUR440 diode is used for D1 and FR307 diode for Di1, the loss value of the diodes is equal to:

$$P_{cond-loss\ \ D1} = I_{ave-D} \times V_F = 0.49 \times 1.05 = 0.515$$

$$P_{cond-loss\ \ Di1} = I_{ave-D} \times V_F = 0.41 \times 1.3 = 0.533$$

It should also be noted that concerning converters 1 and 2, the reverse parallel diode of switch S1 is turned on in mode 4, but since the duration and the passing current is very brief, its losses can be ignored. Switch conductivity losses are calculated based on the following equation:

$$P_{cond-loss} = R_{DS} \cdot \int I_{S-rms}^2 \qquad (22)$$

In this equation, I_{S-rms} is equal to the RMS value and the current passing through the switch in one cycle and R_{DS} is the conductivity resistance of the switch.

3.6. Conductivity losses of conventional flyback converter switches

This converter has one switch S1 in the primary and two switches of Si1 and Si2 in the secondary. If IRFP240 is used for switch S1 and IXFK32N100Q3-ND for switches Si1 and Si2, the amount of conductivity losses of the circuit switches is equal to:

$$P_{cond-loss\,S1} = R_{DS} \cdot \int I_{S-rms}^2 = 0.18 \times 2.643 = 0.476$$

$$P_{cond-loss\,Si1} = R_{DS} \cdot \int I_{S-rms}^2 = 0.32 \times 0.591 = 0.189$$

$$P_{cond-loss\,Si2} = R_{DS} \cdot \int I_{S-rms}^2 = 0.32 \times 0.591 = 0.189$$

3.6.1. Conductivity losses of the proposed flyback converter switches 1

This converter has two switches S1 and S2 in the primary and two switches Si1 and Si2 in the secondary. If IRFP240 is used for switches S1 and S2 and IXFK32N100Q3-ND for switches Si1 and Si2, the amount of conductivity losses of circuit switches is equal to:

$$P_{cond-loss\,S1} = R_{DS} \cdot \int I_{S-rms}^2 = 0.18 \times 2.865 = 0.516$$

$$P_{cond-loss\,S2} = R_{DS} \cdot \int I_{S-rms}^2 = 0.18 \times 1.895 = 0.341$$

$$P_{cond-loss\,Si1} = R_{DS} \cdot \int I_{S-rms}^2 = 0.32 \times 0.643 = 0.206$$

$$P_{cond-loss\,Si2} = R_{DS} \cdot \int I_{S-rms}^2 = 0.32 \times 0.643 = 0.206$$

3.6.2. Conductivity losses of the proposed flyback converter switches 2

This converter has two switches S1 and S2 in the primary and four switches Si1, Si2, Si3 and Si4 in the secondary. Regarding this converter, IRFP240 is used for switches S1 and S2. Concerning this converter, IXFR48N50Q-ND is also used for switches Si1, Si2, Si3 and Si4 [10]. Because the voltage stress of the secondary switches is half of the converter 1, this switch is used which has a voltage of 500 volts and a conductivity of 0.11 ohms. For this converter, the level of conduction losses of circuit switches is equal to:

$$P_{cond-loss\,S1} = R_{DS}.\int I^2_{S1-rms} = 0.18 \times 2.865 = 0.516$$

$$P_{cond-loss\,S2} = R_{DS}.\int I^2_{S2-rms} = 0.18 \times 1.895 = 0.341$$

$$P_{cond-loss\,Si1} = R_{DS}.\int I^2_{Si1-rms} = 0.11 \times 0.643 = 0.071$$

$$P_{cond-loss\,Si2} = R_{DS}.\int I^2_{Si2-rms} = 0.11 \times 0.643 = 0.071$$

$$P_{cond-loss\,Si3} = R_{DS}.\int I^2_{Si3-rms} = 0.11 \times 0.643 = 0.071$$

$$P_{cond-loss\,Si3} = R_{DS}.\int I^2_{Si4-rms} = 0.11 \times 0.643 = 0.071$$

Table 2 shows a comparison of losses between a conventional flyback converter, a proposed soft switching converter and a soft switching converter with a four-switching inverter under the same conditions and 100 watts of power. Switching losses of the secondary switches are very small and are equal to zero because, firstly, these switches are switched at the city power frequency and secondly, the overlap between voltage and current is very low. One type of output filter has been used for all three converters and as a result the output filter losses have been the same [11]. Because the soft switching converter with a four-switching inverter has used a two-winding transformer, its transformer losses have been less. As shown in the table, the soft switching converter losses are less than the hard switching flyback converter and have a greater rate of efficiency. Also, the proposed soft switching converter 2 has the lowest losses. The reason was two-winding transformers were used and lower voltage switches for secondary switches were applied.

Table 2. Comparison of losses between converters.

Type of losses	Equation	Conventional converter	Soft switching converter	Soft switching converter with four-switch inverter
Switching losses S1	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	4.38	0	0
Switching losses S2	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	NA	0	0
Switching losses Si1	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	0	0	0
Switching losses Si2	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	0	0	0
Switching losses Si3	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	NA	NA	0
Switching losses Si4	$\frac{1}{2}V_{ds}I_d(t_{on}+t_{off})f_{ws}$	NA	NA	0
Conductivity losses S1	$R_{DS}.\int I_S^2$	0.476	0.516	0.516
Conductivity losses S2	$R_{DS}.\int I_S^2$	NA	0.341	0.341
Conductivity losses Si1	$R_{DS}.\int I_S^2$	0.189	0.206	0.071
Conductivity losses Si2	$R_{DS}.\int I_S^2$	0.189	0.206	0.071
Conductivity losses Si3	$R_{DS}.\int I_S^2$	NA	NA	0.071
Conductivity losses Si4	$R_{DS}.\int I_S^2$	NA	NA	0.071
Conductivity losses D1	$I_{ave-D} \times V_F$	NA	0.515	0.515
Conductivity losses Di	$I_{ave-D} \times V_F$	0.268	0.273	0.533

Conductivity losses Di2	$I_{ave-D} \times V_F$	0.268	0.273	NA
Transformer losses	-	1	1	0.8
Output filter losses	-	1	1	1
Sum of losses	-	7.77	4.33	3.99
Efficiency	-	92.23%	95.67%	96.01%

4. Conclusion

Because of the switching and EMI losses and the high switching stress in the flyback inverter, it is not possible to increase the switching frequency of this converter. Using a higher switching frequency reduces the size of the output filter, makes it easier to remove harmonics, and eliminates audible noise. One way to reduce a converter voltage stress is to use a snubber. However, snubber does not reduce switching losses while only removes losses from the switch. For this end, soft switching inverters should be used at high frequencies. The following results are suggested as soft switching methods are used in the flyback inverter:

1. Increasing switching frequency
2. Reducing switching losses
3. Increasing efficiency
4. Reducing EMI noise
5. Reducing the stress from the inverter switches
6. Increasing the life of inverter switches

To eliminate the drawbacks of previous inverters, a new inverter flyback with soft switching competency was proposed. The auxiliary circuit is made of a switch, a diode, a capacitor and two auxiliary inductors. This inverter has the following specifications:

1. The inverter has a simple auxiliary circuit.
2. The main switch turns on and off at a zero current.
3. The secondary switches turn on at a zero voltage.
4. The auxiliary switch changes modes in a zero current
5. The inverter can operate with DCM and BCM methods and switching can be performed at any time.
6. Using the auxiliary circuit, the voltage stress of the main converter switch is reduced.
7. By reducing the switching losses of the circuit, a higher frequency can be used in the converter.

As the switching frequency increases, the volume and weight of the converter decreases.

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