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An Efficient Grid-tied Flyback Micro-inverter with DCM Control Strategy

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Abstract

In two-stage micro-inverter photovoltaic (PV) applications, DC/DC converter is used to obtain the highest DC power from the PV module. In this type of inverter, the rising of voltage from the PV module to a grid voltage level is limited to a certain value. Moreover, the absence of the isolation between the input and output makes it is less efficient. For these reasons, an efficient single-stage grid-tied flyback PV micro-inverter with discontinuous conduction mode (DCM) control strategy is proposed to feed an alternating current (AC) to the main grid with a lower value of the total harmonic distortion (THD). The control strategy is based on a sine sinusoidal pulse width modulation (SPWM) technique to control the main switch of flyback inverter. Also, a simple perturb and observe (P&O) maximum power point tracking (MPPT) technique has been presented to obtain the MPP point from the PV module for any environmental conditions. The proposed control was verified using PSIM software and simulation results is obtained. The proposed control is tested under different weather conditions for solar irradiance and temperature, as a result, a pure sin wave current has been injected into the grid with a lower harmonics value. Finally, the small size, low cost and high reliability of single stage flyback micro-inverter is presented without the need for DC/DC converter.

Keywords: Single-stage micro-inverter; Grid-tied Micro-inverter; flyback inverter; DCM control strategy; SPWM control; and PSIM simulation.

1. Introduction

Nowadays, renewable energy is considered the attractive solution to solve most problems in fuel fossil energy. Thus, renewable energy harvested by solar photovoltaic (PV) system is among the fleet of new generating technologies driving the demand for the generation of electricity [1]. The PV applications can be divided into two categories: the on-grid and the off-grid applications [2]. In the first type, the PV application is connected to the utility grid with the same frequency, amplitude, and phase of the grid. On other the hand, the stand-alone or off-grid PV system which supplied the power requirements to different loads such as alternating current (AC) loads, and direct current (DC) loads, or the batteries. The grid-connected inverters represent the main part of the PV system that is used to integrate with the grid.

Recently, several researchers have studied and reviewed the grid-connected inverters. In general, three types of grid-connected inverters are used today, which are micro-inverters, string inverters, and central inverters as presented in Fig.1 [3]. The central inverters type is considered simple and inexpensive. A few numbers of inverters are connected with many number of PV modules. Thus, it is more efficient than the string inverter but at the same time it is failing in the shading effects of the PV modules. While the string inverters are used for just one string of modules such as eight modules connected with series. Fewer inverters are required for a large number of PV modules. A lower efficiency is obtained in these inverters due to a one MPPT technique implemented for all PV modules in the same time. Compared with the previous types, the micro-inverters represent an attractive solution for low power applications. It is more expensive than the other

Nomenclature

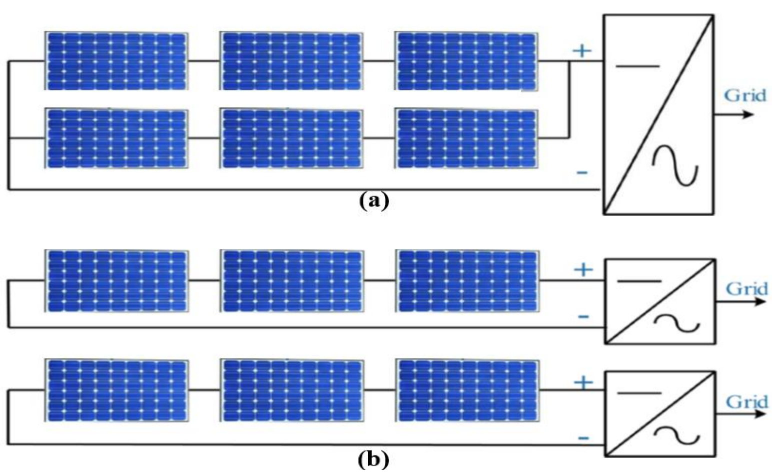
AC	alternating current	MPPT	maximum power point tracking
DC	Direct current	MOSFET	metal oxide semiconductor field effect transistor
DCM	discontinuous conduction mode	PI	proportional-integral
G	solar irradiance	PF	power factor
IGBET	insulated gate bipolar transistor	P&O	perturb and observe
PV	photovoltaic	T	temperature
PWM	pulse width modulation	THD	total harmonic distortion
PSIM	power simulation software	ZCD	zero-cross detection
SPWM	sine sinusoidal pulse width modulation		

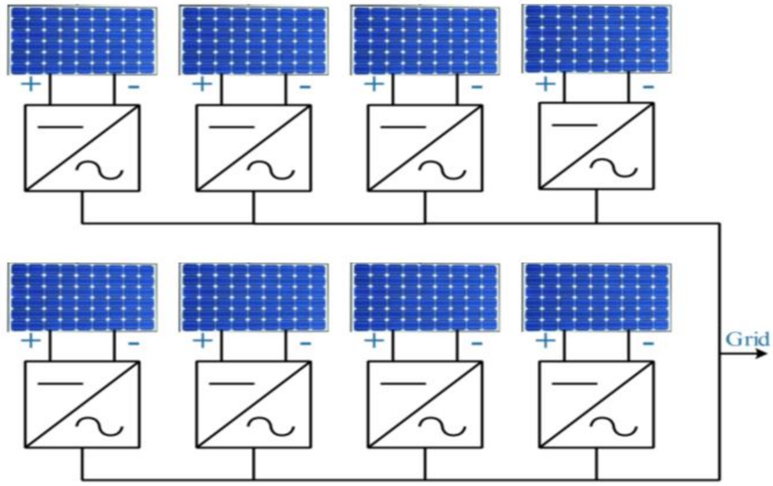
Symbols

C_{in}	input capacitor	k_P	proportional gain
C_f	filter capacitor	P_o	output power
D_1, D_2	secondary side diodes	S_1, S_2	Secondary side switches
D_{max}	maximum duty cycle	S_{PV}	main MOSFET
$e(t)$	error of PI controller	$S(t)$	high frequency sawtooth signal
f	grid frequency	$SR(t)$	sinusoidal reference signal
f_s	switching frequency	T_{on}	ON time period
I_1	main MOSFET current	$T_{on,max}$	maximum ON time period
I_2	current through S_1	T_{off}	OFF time period
$\hat{I}_p$	peak primary current	$T_{off,max}$	maximum OFF time period
I_{s1}	the first secondary current	$u(t)$	output of PI controller
I_{s2}	the second secondary current	V_{pv}	PV voltage
I_s	the total secondary current	$\hat{V}_g$	peak grid voltage
$I_{out,rms}$	RMS output current	V_{rms}	RMS grid volateg
I_p^*	peak primary current	Δ_v	ripple in PV voltage
I_{mp}	maximum power current	Δ_i	ripple in PV current
K_I	integral gain	η	efficiency

inverters, but provides high efficiency and reliability. In recent years, many technologies are proposed to design the small and efficient micro-inverter [4-10]. Flyback micro-inverter [11-16] represents a good attractive micro-inverter that is integrated with a single PV module. By incorporating this configuration, the possibilities of operating a system, based on a "plug and play" device. Thus, the small size and high reliability are obtained through this micro-inverter due to having only single-stage power conversion without the need for DC/DC converter in their inverter.

Therefore, in this paper, a flyback PV micro-inverter is presented due to many benefits such as it can directly convert the sufficient DC power to AC power, amplification of low DC input voltage level to high voltage level, and low cost with high reliability. The DCM control strategy is used to control the injection current to the grid with the SPWM technique. Also, PSIM software is used to simulate the proposed micro-inverter to perform its performance under different weather conditions. Since a high performance is achieved with that technique during feeding the current to the grid with different weather conditions. Finally, a pure sine wave current is injected to the grid with a low content of THD.





(c)

Fig.1. PV inverter types (a) Central inverters (b) string inverters (c) Micro-inverters

2. Grid-tied Flyback Micro-inverter

A flyback micro-inverter is considered a suitable choice for grid connected PV applications due to having more advantages such as single stage conversion, isolation and reliability, which its circuit is presented in Fig.2 [17-19]. For this reason, this micro-inverter is studied and analyzed in this paper. The operation modes of this inverter during one switching period is indicated in the following:

Mode I: if the main switch, S_{PV} is ON state, the PV voltage is impressed during the primary winding of the transformer, and store energy in inductance of the transformer, L_m which causes the primary current to ramp up to reach its maximum value. The other switches are OFF and the filter capacitor, C_f is discharged to the utility grid.

Mode II: When the, S_{PV} is OFF state, the stored energy will be released to the AC utility grid that has positive polarity by turning ON the switch, S_1 and D_1 with all other switches OFF.

Mode III and **Mode IV**: These modes clarify the negative half cycle, where S_{PV} operates alternately at a high switching frequency. Therefore, in mode III, S_{PV} again conducts and energy is stored in the transformer, then this energy is transferred to the AC utility grid through the switches, S_2 and D_2. Furthermore, output current through switch, S_1 in the positive half cycle is controlled the same as in the negative half cycle. Moreover, the output current is either released through, S_1 and D_1 as positive or through S_2 and D_2 as negative. The duty cycle of S_{PV} should vary with the grid voltage.

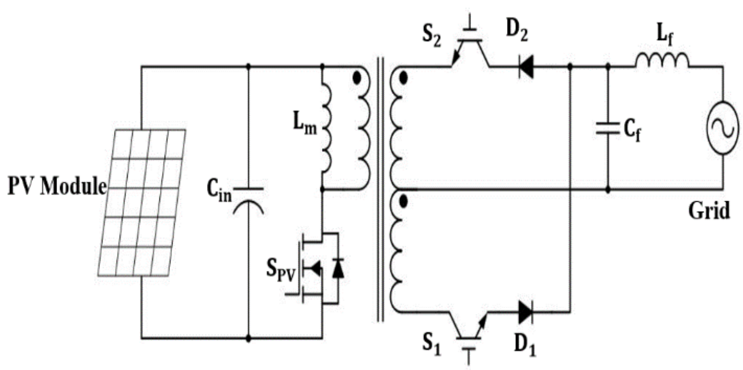


Fig.2. Electrical circuit of grid-tied flyback-micro-inverter**.**

3. Proposed DCM Control Strategy

3.1. Design of SPWM Technique

The DCM control, the switching frequency stays constant. This is done by comparing the primary reference current, I_p^* that is generated by multiplication of a sinusoidal reference $SR(t)$ signal, and the maximum current of PV module, I_{mp} through the Proportional-Integral (PI) controller with the high frequency sawtooth signal, $S(t)$ to generate sequence of the gate pulses to, S_{PV} through the PWM modulator as presented in Fig.3.

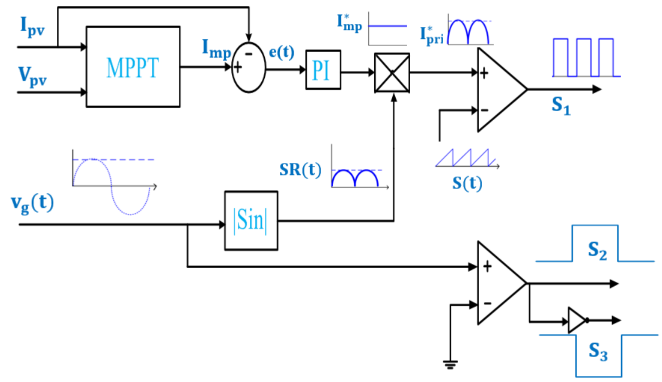


Fig.3. proposed DCM control strategy.

On the other hand, the secondary switches are triggered reciprocally with the utility grid polarity by the low line frequency (50Hz) PWM generator. The utility grid voltage is sensed by using zero-cross detection method (ZCD) for synchronizing the flyback inverter with the grid as a sinusoidal reference, SR(t) which controls waveform for the generated PWM signal of S_{PV}. The amplitude of SR(t) is adjusted by the value of the maximum current of the PV module that is tracked by the MPPT technique. Figure 4 presented the switching sequence and waveforms of flyback micro-inverter for DCM operation. However, the maximum duty cycle of the main switch can be determined as [20-23],

$$D_{max} \leq \frac{1}{\frac{V_{pv}N}{\hat{V}_g}+1} \qquad (1)$$

Where V_{pv} is the PV voltage, $\hat{V}_g$ is the peak grid voltage, and N is the turns-ratio. In order to stay always under DCM operation, the OFF time interval T_{off} should be smaller than the period between the total time interval and the ON time interval, T_{on} that gives [23,24]:

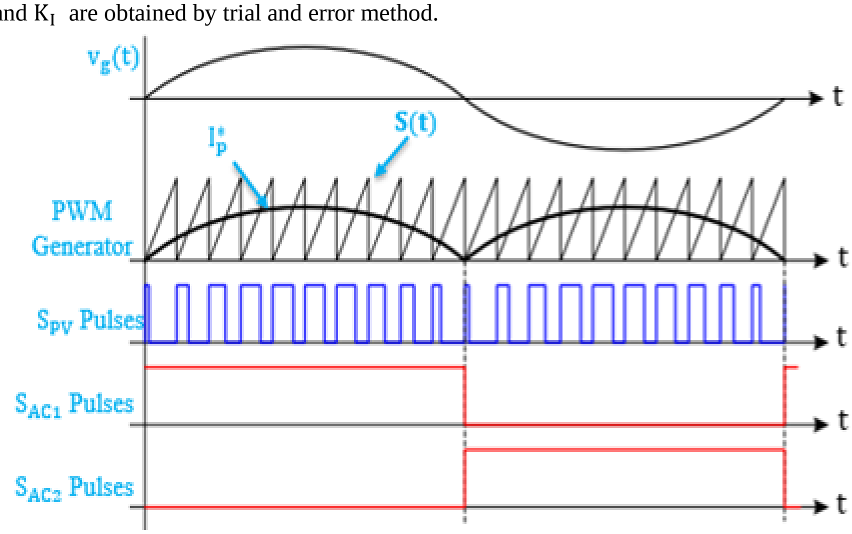
$$T_{off,max} \leq (T_s - T_{on,max}) \qquad (2)$$

3.2. Design of PI-MPPT Controller

The nonlinear characteristics of the PV module due to solar irradiation and ambient temperature are considered the major problem in reducing the PV efficiency. Therefore, several researchers have proposed the MPPT technique to obtain a peak power from the module and then increase its efficiency. A large number of the techniques are proposed making it difficult to select the best technique to adopt when implementing a PV system [20-25]. Most of the conventional MPPT techniques are used in the voltage-source converter which are usually designed by regulating the PV voltage. Since, the main principle action of flyback inverter is operated as a sinusoidal current-source inverter and the input voltage cannot be directly controlled, which depends on PV module characteristics. For this reason, in this paper, the P&O method is used and realized by adjusting the current of the PV module. The basic algorithm of this method is shown in Fig. 5. However, the objective of the PI controller is to adjust the DC output current of the MPPT controller. The output current from MPPT, I_{mp} is compared with the current that is extracted from the PV module, I_{pv}, then the error is decreased to approximately zero by the PI controller. The output of PI controller, I^*_{mp} is multiplied by a sinusoidal reference waveform, SR(t).The PI controller algorithm in time domain can be written as [26]:

$$u(t) = K_P\, e(t) + K_I \int_0^t e(\tau)d\tau \qquad (3)$$

where u(t) is the output, K_P is "the proportional gain", K_I is "the integral gain", and e(t) is the error between the reference value and measured value. In this paper, K_P and K_I are obtained by trial and error method.



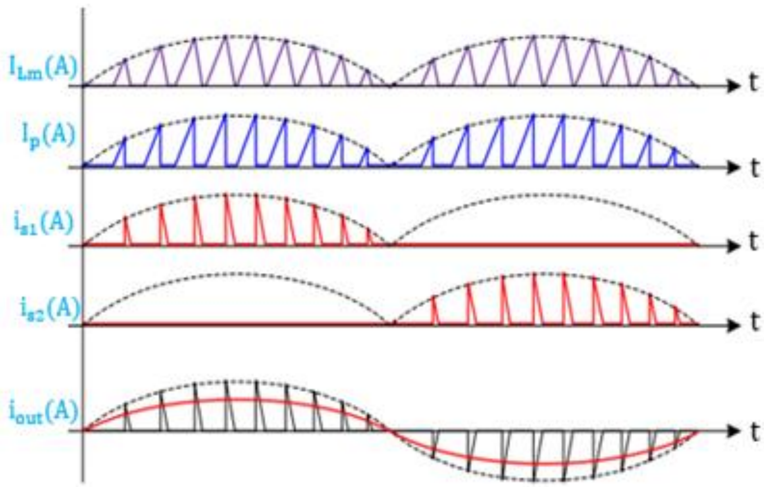


Fig.4. switching waveforms of flyback micro-inverter at DCM control

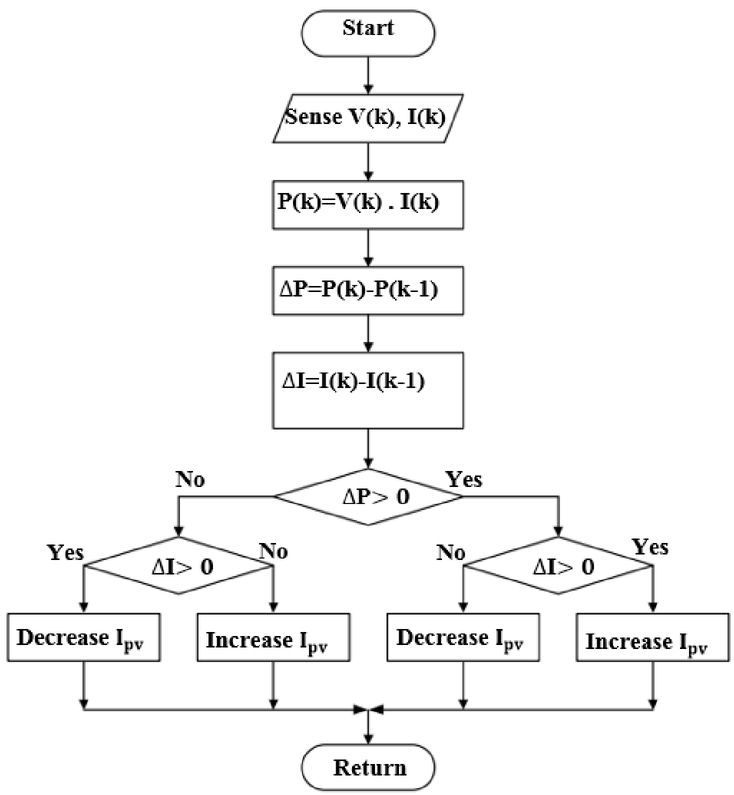


Fig.5. the flowchart of P&O MPPT technique.

4. Simulation Results and Discussion

To investigate the performance of the proposed control strategy, the power simulation program (PSIM) is used to simulate the micro-inverter. The controller and power circuit parameters that have been analyzed and designed in this paper are used to construct the simulation model. Table 1 shows the parameters of the proposed circuit. Figure 6 shows the simulation model of the flyback micro-inverter based on PSIM for 150W.

Table 1. Parameters of the proposed circuit.

Parameter	Value	Unit
$P_{o,max}$	150	W
$V_{g,rms}$	220	V
f	50	Hz
f_s	30	kHz

V_{pv}	33-38	V
C_{in}	11000 μF,50V	-
N	10	-
L_m	15.13	μH
η	0.92	-
K_P	10	-
K_I	0.001	-

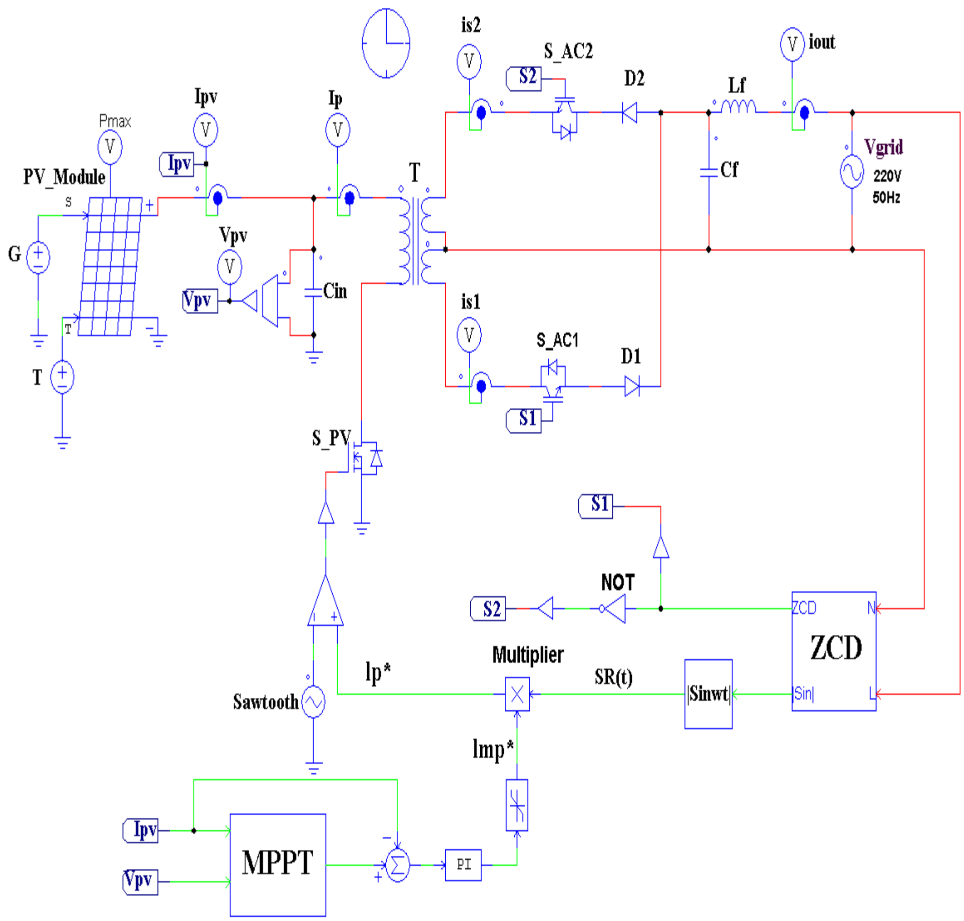


Fig. 6. Proposed Flyaback micro-inverter model in PSIM.

Figure 7 shows the output voltage from the PV module,V_{pv} = 35 V it has a little of ripple about, Δ_v= 1.5 V. Since, this ripple on the input will cause distortion, and lead to increasing THD. Furthermore, the main factor that causes the ripple in flyback is the instantaneous power fluctuation that has twice of an average power magnitude and twice of the grid frequency. This ripple is filtered by using a large decoupling capacitor, C_{in} (11000μF, 50V) connected across input side which represents a simple power decoupling method. The output current from PV module can be shown in Fig.8, whose value I_{pv} = 4.66 A, and has small ripple of Δ_i= 0.1 A.

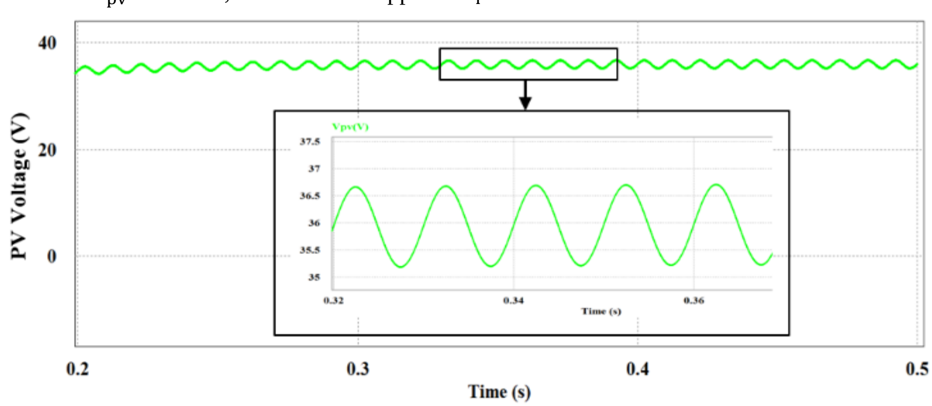


Fig.7. The output voltage from PV module

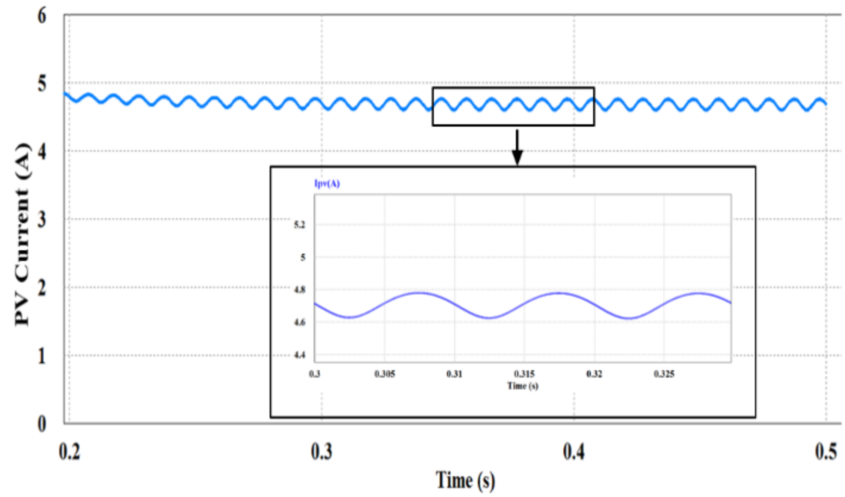


Fig.8.The output current from PV module.

Figure 9 shows the gate pulses sequence for the main switch, S_{PV} (MOSFET) and the secondary switches, S_1 and S_2 (IGBTs). Figure 10 shows operating currents in the proposed inverter. Figure 10-a shows the primary current which has a rectified sine wave due to the sinusoidal modulation, whose value is $\hat{I}_p = 32.8A$. Figure 10-b shows the first secondary current, I_{s1} that flow during, S_1 and D_1 at the positive half cycle, whose peak value is, $\hat{I}_{s1} = 3.5A$. Figure 10-c shows the second secondary current, I_{s2} that flow during S_2 and D_2 at the negative half cycle. The peak value of this current, $\hat{I}_{s2} = -3.5$ A. Figure 10-d shows the total secondary current, i_s which represents the output current that is injected to the utility grid without C-L filter. The total secondary has RMS value that is $I_{s,rms} = 0.9$ A.

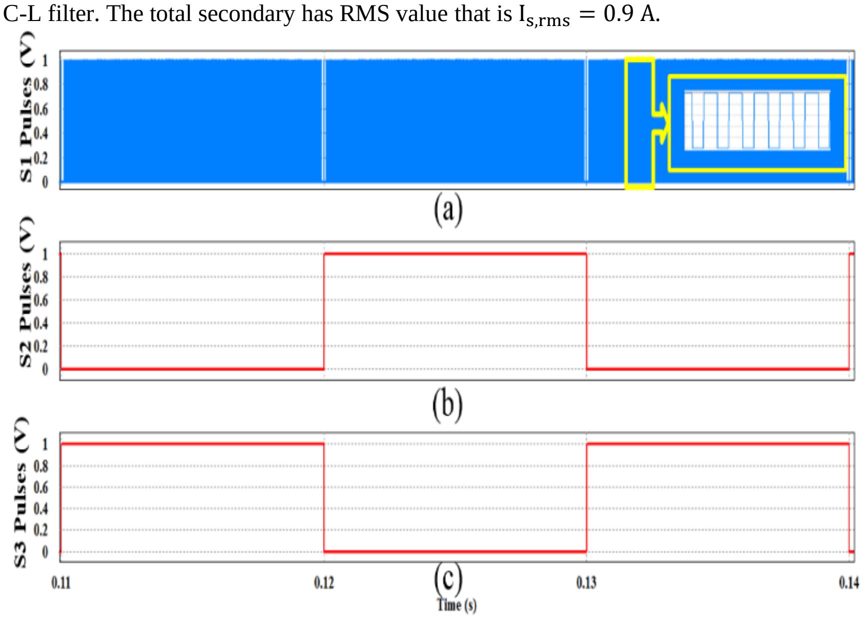
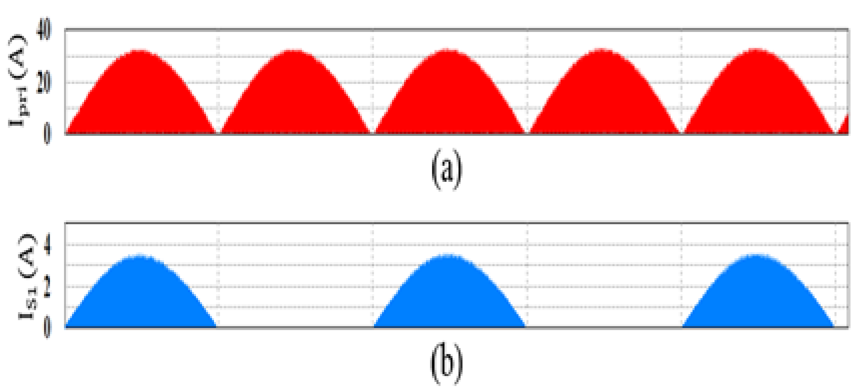


Fig.9. The PWM pulses (a) S_{PV} gate pulses. (b) S_1 gate pulses. (c) S_2 gate pulses



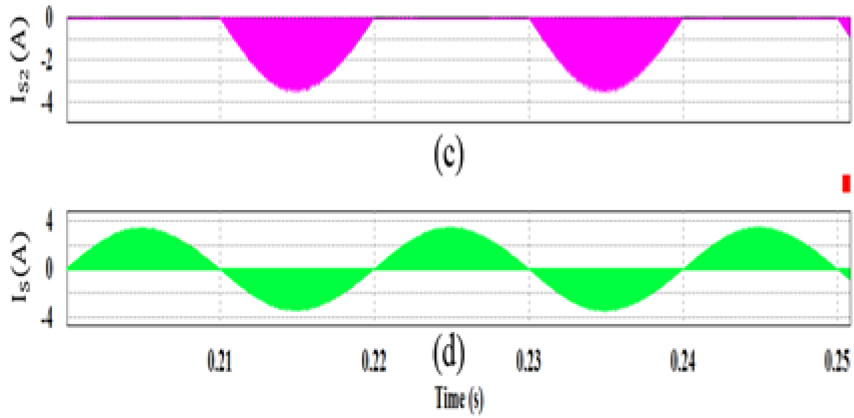


Fig. 10. Currents waveforms of the proposed micro-inverter (a) The primary current, I_P (b) The first secondary current, i_{s1}. (c) The second secondary current i_{s2}.(d) The total secondary current, i_s.

Figure 11 indicates the current stress in the main switch, S_{PV} and current stress in S_1 multiplied by 5. The current in S_{PV} has a triangular like shape , when S_{PV} is ON state, therefore this current ramps up until it reaches to peak value and fall down to zero at the end of ON time interval. The peak value of this current is $\hat{I}_1 = 32.8$ A. The current in secondary switch, S_1 has fell down from peak value at the end of ON time interval until it has reached zero. The peak value of this current is $I_2 = 3.5$ A.

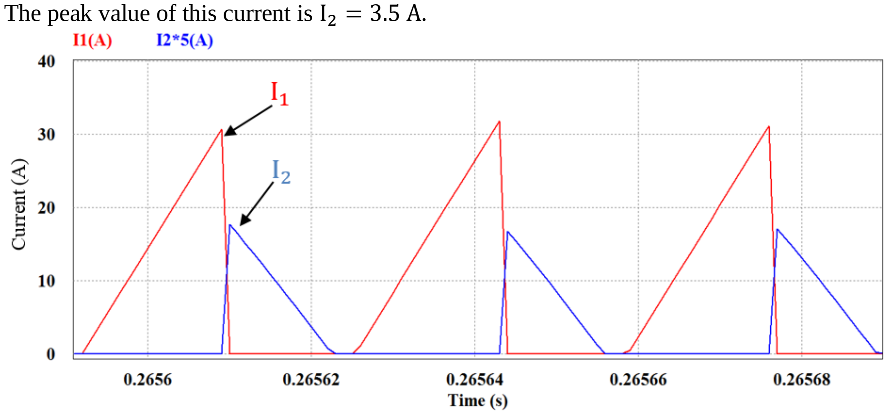


Fig.11. The main switch, S_{PV} current and secondary switch, S_1 current.

Figure 12 indicates the input power and output power of the flyback micro-inverter, $P_{pv} = 163$ W, which represents the output power from PV module and input power to the micro-inverter. On other hand, the output power from the micro-inverter, which transferred to the grid, $P_o = 150$ W for solar irradiance $G = 750 W/m^2$ and temperature $T = 20°C$. Figures (13-15) indicates the injection current to the utility grid from flyback micro-inverter with CL filter. Figure 13 shows the output current for $G = 750\ W/m^2$ and $T = 20°C$. Whose RMS value is ,$I_{out,rms} = 0.68$A, and it is almost in-phase with the grid voltage by power factor of $P.F = 0.98$ and low value of $THD = 3.36\%$. Figure 14 shows the output current for $G = 650\ W/m^2$ and $T = 20°C$. whose RMS value,$I_{out,rms} = 0.56$A, power factor $P.F = 0.977$ and $THD = 3.5\%$. Figure 15 shows the output current for $G = 400\ W/m^2$ and $T = 30°C$ whose value,$I_{out,rms} = 0.23$A, power factor of $P.F = 0.95$ and $THD = 4\%$. To investigate the control method, THD comparison between the theoretical and simulation results are done as presented in Fig.16 with respect the real output power injected to the grid.

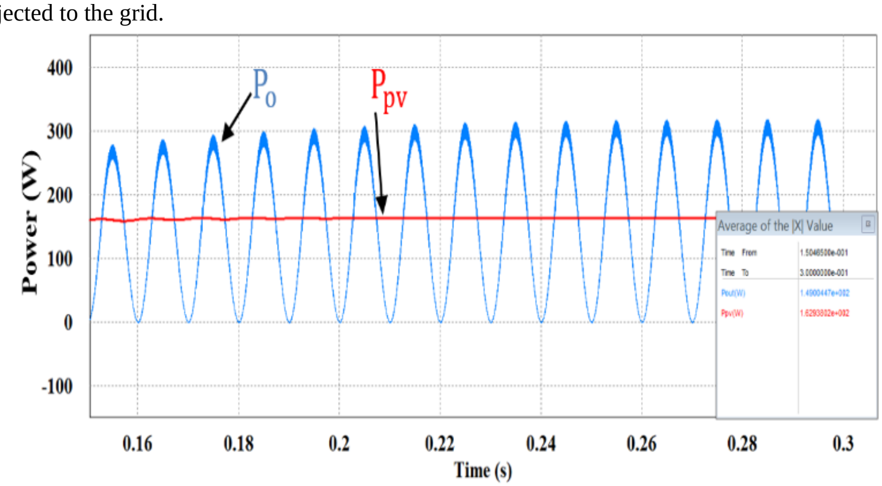


Fig.12. Input and output power of flyback micro-inverter

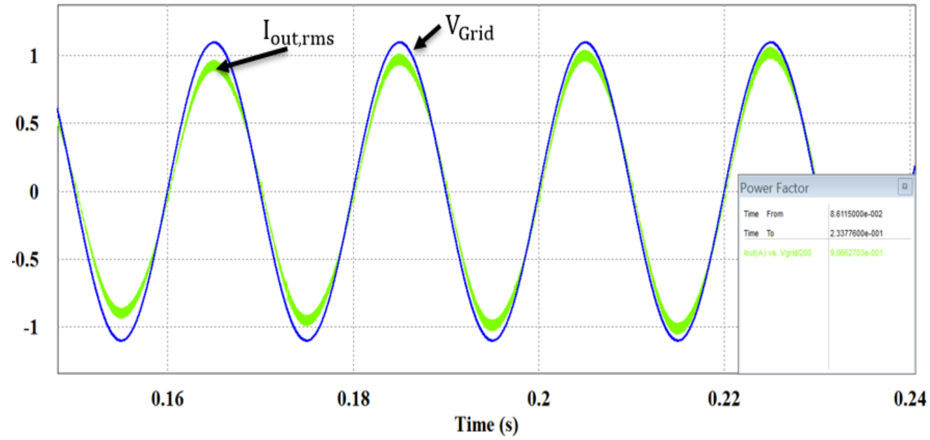


Fig.13. The output current fed to grid with CL filter, $I_{out,rms} = 0.68A$

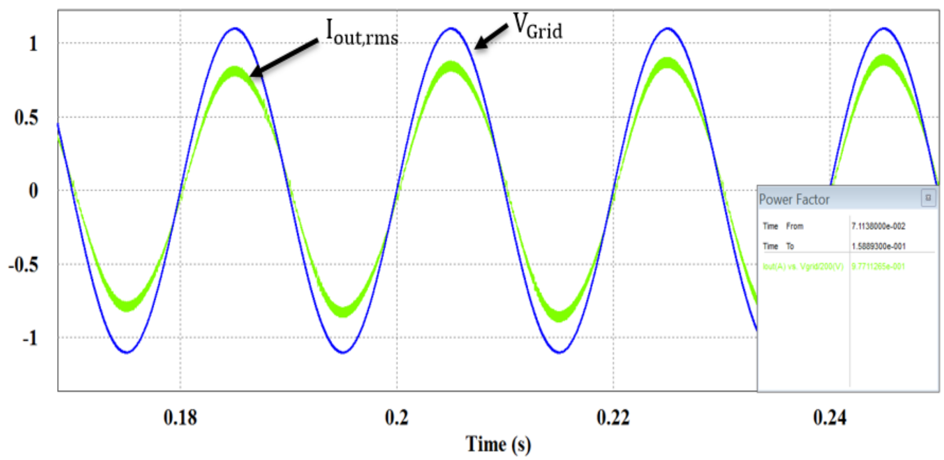


Fig.14. The output current fed to the grid with CL filter, $I_{out,rms} = 0.56A$

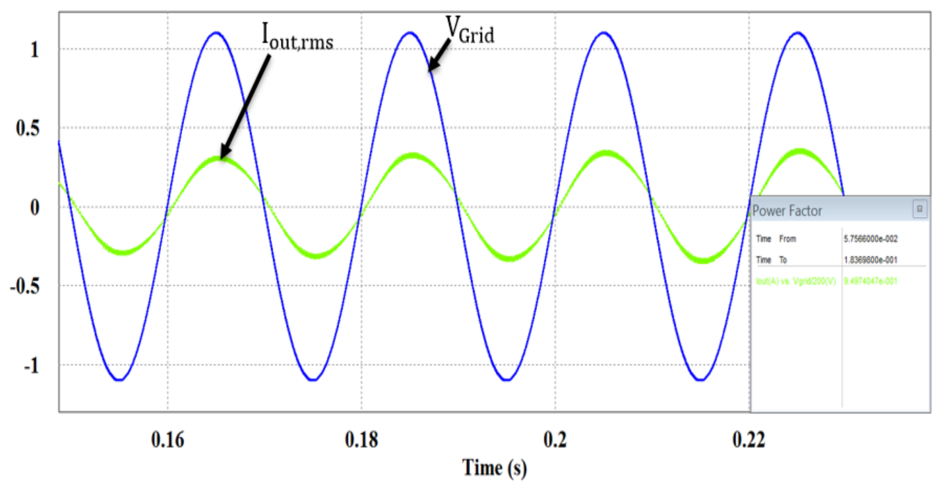


Fig.15. The output current fed to the grid with CL filter, $I_{out,rms} = 0.23A$

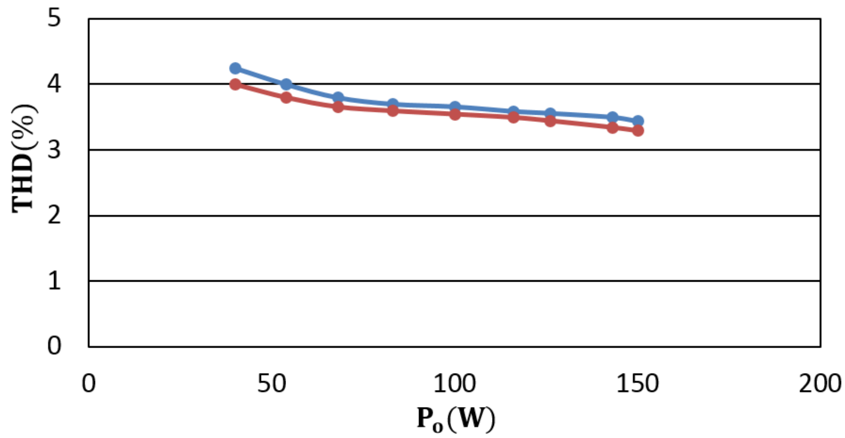


Fig.16. THD comparison between the theoretical and simulation results.

5. Conclusion

In this paper, an efficient grid-tied micro-inverter is presented. In this work, a single-stage flyback micro-inverter with a DCM control strategy is proposed to feed a pure sine wave current to the utility grid with lower THD content. The proposed control strategy is based on the SPWM technique, which offers a pure sine wave current, compared with that of the traditional method of PWM technique. The SPWM technique is used to produce a suitable gate signal to the main switch of flyback circuit. Moreover, the simple P&O MPPT technique is used to obtain the MPP point from the PV module under different weather conditions. To confirm our control strategy, the PSIM software is used to test the strategy performance under different environmental conditions. Hence, compared with a two-stage grid-tied micro-inverter circuit, the proposed micro-inverter offers low cost and small size due to having an isolated single-stage DC/AC conversion without the need of a DC/DC converter.

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