Optimal Design and Analysis of Single-Stage Flyback PV Micro-inverter

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The European Conference on Sustainability, Energy & the Environment 2018
Official Conference Proceedings

Abstract
Over the last decades, solar energy systems have aroused much interest due to increased concern for the environment. Photovoltaic (PV) module based electric power generation systems present promising solutions to ensure sustainable, abundant, inexhaustible, and environmentally friendly energy. In view of the foregoing, converters used in PV systems is emerging as a major component. Micro-inverters (MIs) known as module based type of inverters, which are attached to individual PV modules as an operative interface between PV and utility grid, provide an efficient, reliable, and cost effective power generation possibility. The salient features of MIs can be expressed as lower installation cost, improved energy harvesting by allowing individual maximum power point tracking (MPPT), plug-N-play operation, and improved system efficiency. This paper presents a detailed analysis of modelling and control of single-phase grid connected single-stage flyback PV MI. A 205W single-stage flyback MI is investigated with respect to power circuit design and component selection criteria, operation modes, MPPT control, injected grid current control, and grid synchronisation. To assess and validate feasibility of analysed 205W single-stage flyback MI, a simulation model is constructed by using an electromagnetic transient software package PSCAD/EMTDC.

Keywords: Very-short term, Energy forecasting, Household, Smart grid integration, Artificial intelligence, Decision trees, Genetic algorithm, Artificial neural networks, Support vector machines, Mean absolute error

Introduction

The energy source demand for the electricity generation grows over the world for the past decades and will continue to grow in the forthcoming decades. The shortcomings of the sources used for electricity generation include coal, natural gas, petroleum, and other liquid fuels aroused much interest for renewable energy sources. Also, utilisation of these sources reveals a huge environmental problem named as global warming, which is one of the most significant threats for future of global climate change. In this manner, the renewable energy sources play an important role for the future of humanity due to being sustainable, abundant, inexhaustible, and environmentally friendly (Çelik et. al, 2018). An evaluation of the current state-of-cumulative installed renewable energy capacity for different renewable energy technologies are given in Figure 1.

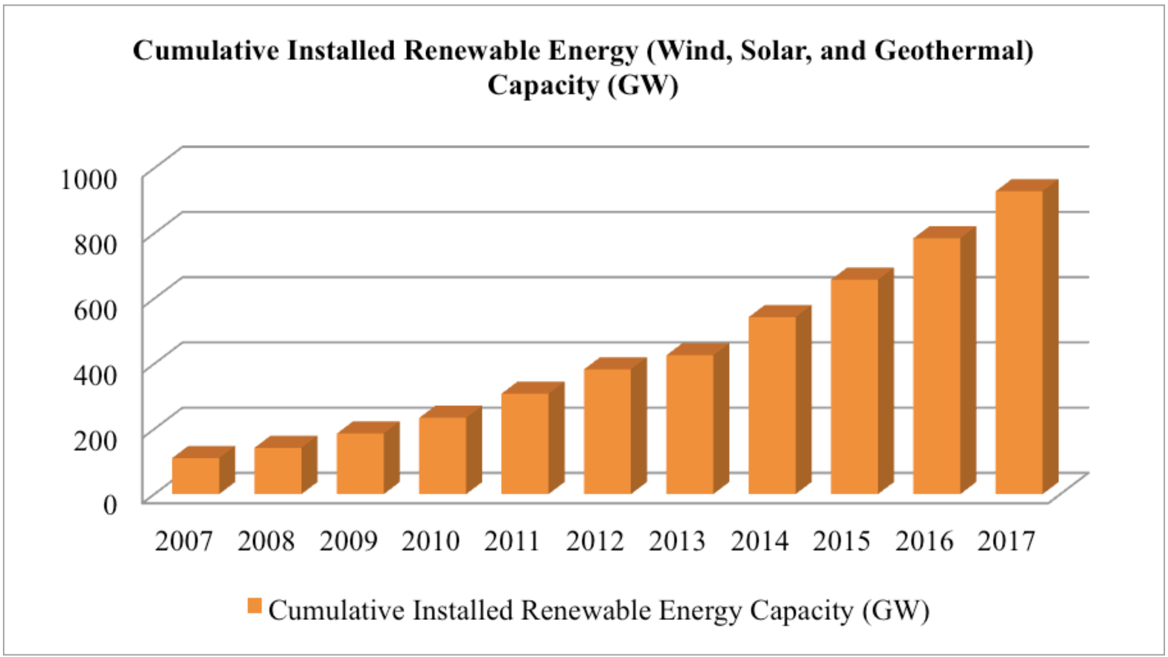


Figure 1. The cumulative installed renewable energy capacity (BP, 2018)

Among the renewable energy sources, solar energy gains acceptance in terms of being applicable in almost every place that is convenient for placement of PV panels and demonstrates exponential growth with the support programs of governments. When the cumulative installed capacity of mostly utilised renewable energy sources is investigated, solar energy can be considered as one of the most promising source of energy and constitutes 43% of total installed renewable energy capacity as shown in Figure 2 (Hasan et. al, 2017).

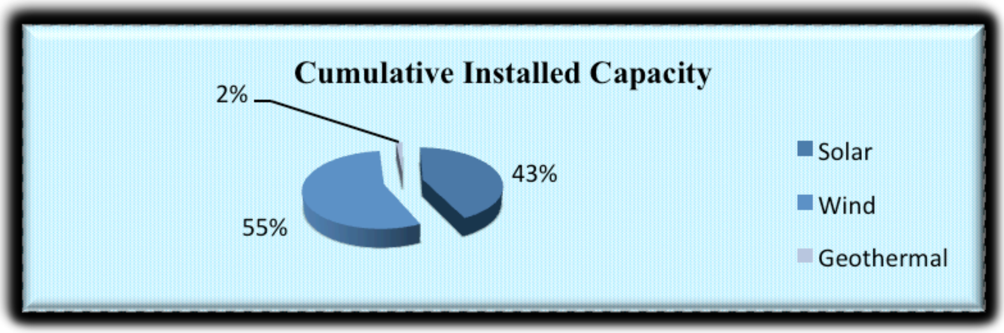


Figure 2. Percentage of solar energy among the renewable energy sources (BP, 2018)

The total installed capacity of PV systems exceeds 400 GW at the end of 2017. The tremendous potential of PV systems can be clearly seen from the Figure 3. Especially in 2017, deployment of solar power had a very strong year by showing an increase of about 100 GW.

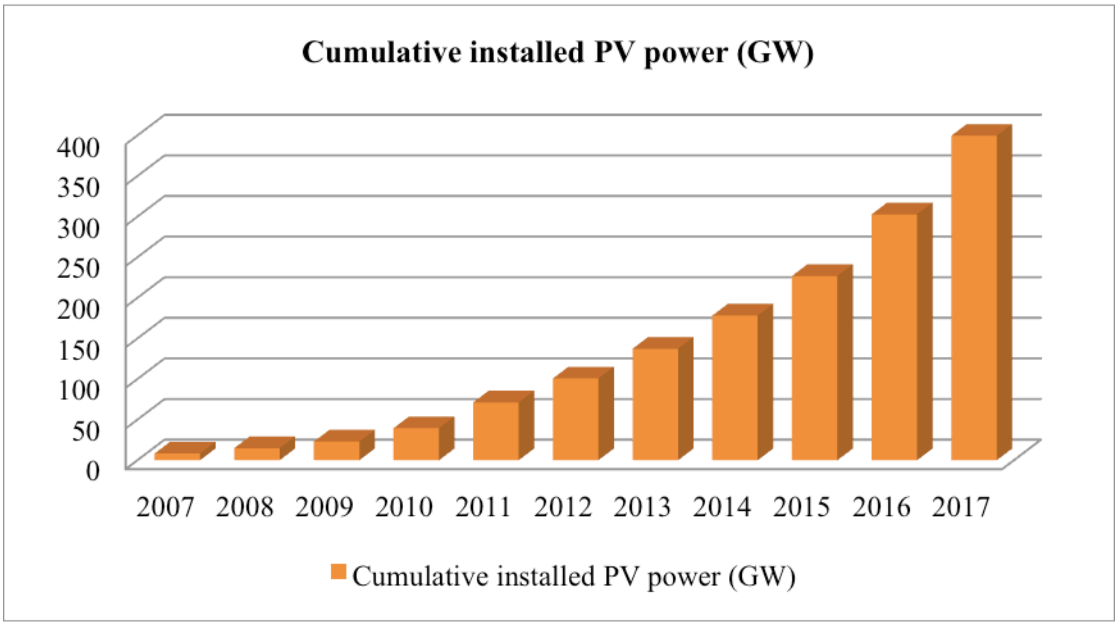


Figure 3. Cumulative installed PV power (BP, 2018)

Besides having so many merits such as easy to install, no noise, almost maintenance free, inexhaustible, and environmentally friendly, PV systems suffer from the initial cost of purchasing and installing PV panels (Çelik et. al, 2015). The rapid cost decline and efficiency increment for PV technologies is critical. In addition to studies carried on increasing PV cell efficiency, researching on power electronics based devices for efficient energy harvesting is an effective and economical way to enhance the overall PV system efficiency (Salam et al., 2013; Sher and Addoweesh, 2012; Çelik and Teke, 2017). Inverters can be considered as one of the key components of the PV systems. The configurations of the PV panels and appropriate inverter selection have a direct effect on cost and efficiency of the entire system. Depending upon the solar panel placement, the PV system can be configured in four different types. There are centralised inverters, string inverters, multi-string inverters, and module based inverter also known as MI configurations available as demonstrated in Figure 4.

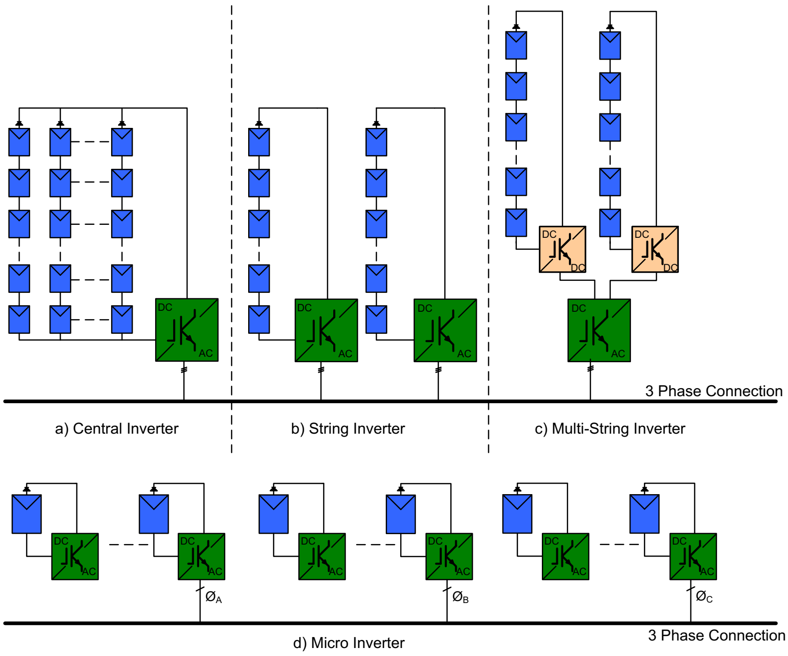


Figure 4. Different inverter design configurations

The MIs are becoming more and more popular for small-scale power applications with the benefits of having better overall efficiency, possibility to become plug-N-play device, lack of DC connections, alleviation of arc and firing risk, eliminating the mismatch losses between the PV panel and the inverter, and having individual MPPT controller (Kyritsis et al., 2008; Zhang et al., 2013). Having individual MPPT controller will attain maximum power from PV modules independent of the atmospheric conditions and partially shading conditions (Çelik and Teke, 2017). The MIs are mostly designed for a power rating between 50 and 400 W with power conversion efficiencies above 90% (Çelik et al., 2018; Hasan and Mekhilef, 2017; Trujillo et al., 2016). Many converter topologies that contain either a single or multi-stage power conditioning system have been developed for the MIs (Lai et al., 2016). In single stage configuration, it is aimed to achieve MPPT control, voltage regulation and DC to AC conversion in a single-stage. Recently, the single-stage flyback MIs shown in Figure 5 emerges as an attractive choice for PV applications.

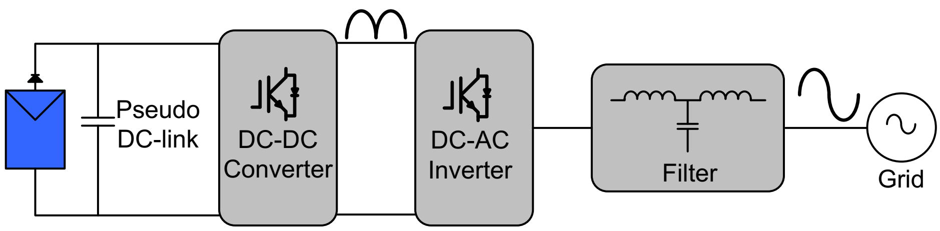


Figure 5. Block diagram of the single-stage MI

The promising aspects of the single-stage flyback MI can be expressed as requiring fewer electronic equipment, high efficiency, having galvanic isolation, high reliability, low volume, and robust control structure with simple design (Edwin et al., 2014; Gao et al., 2014; Kyritsis et al., 2008; Nanakos et al., 2015). In single-stage topology, the decoupling capacitor is placed at the input side and it is expected to perform both MPPT and rectified sine current shaping operations in one stage.

Rectified sinusoidal waveform is delivered to the network by H-bridge unfolder stage and output filter. This configuration is also known as MIs with pseudo DC-link.

In this paper, the flyback inverter operating in discontinuous conduction mode (DCM) is investigated with analytical equations. A detailed analysis of modelling and control of the single-phase grid connected single-stage flyback PV MI is presented. A 205W single-stage flyback MI is investigated with respect to power circuit design and component selection criteria, operation modes, MPPT control, injected grid current control, and grid synchronisation. To assess and validate feasibility of analysed 205W single-stage flyback MI, a simulation model is constructed by using an electromagnetic transient software package PSCAD/EMTDC.

Circuit Topology of Current Source Flyback Inverter and Operation

The circuit topology of the studied DCM operated current source single-stage flyback MI is shown in Figure 6. Due to performing both MPPT and rectified sine current shaping operations in DC-DC converter part, the model is expressed as single-stage.

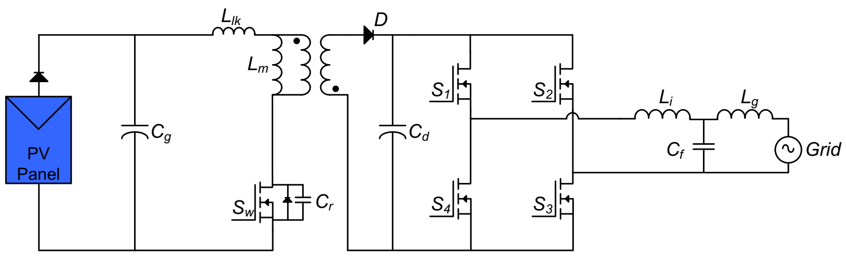


Figure 6. Circuit topology of current source single-stage flyback MI

DCM operation is widely used in flyback MI module applications. This operation mode has three time interval and peak current value of each switching cycle is proportional to the sinusoidal envelope. In the first time interval, transformer is charged during the on time and then in the second time interval, the transformer is discharged during the off time. In the third time interval between the off time and beginning of the switching cycle, there is no current flow through the transformer (Kyritsis et al., 2008). Ensuring zero current turn on of main switch of flyback converter and turn off of output diode reduces the switching loss and eliminating the reverse recovery problem. Also, DCM operation eliminates right half plane (RHP) zero causing difficulties to stabilize the control loop for wide input voltage range. However, the peak value of the magnetising current is high when compared to continuous conduction mode (CCM) and boundary conduction mode (BCM). The high magnetising current rating increases the winding losses of transformer, conduction loss, and switching loss. This operation contains fixed frequency and variable duty cycle that changes according to the reference signal taken from the MPPT controller (Lai, 2014). The block diagram of the control circuit for the DCM operation is given in Figure 7.

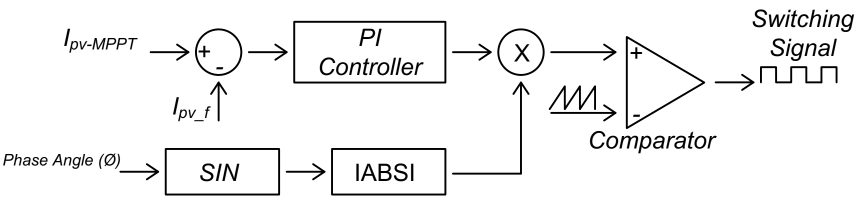


Figure 7. Block diagram of the control circuit for the DCM operation (Kyritsis et al., 2008)

In order to provide the converter to operate in DCM, the condition given in the Eq. 1 should be ensured as

$$t_{off-pk} \leq T_s - t_{on-pk} \tag{1}$$

where "t_{off-pk}" is the switch off time, "t_{on-pk}" is the switch on time, and "T_s" is the switch cycle time.

The current passing through the transformer drop to zero when the main switch is off. When the main switch is off, the voltage reflected to the primary of the transformer will be

$$V_{grid} = V_{grid-pk} \sin(wt) \tag{2}$$

where "V_{grid}" is the grid voltage and "$V_{grid-pk}$" is the peak grid voltage.

For the DCM operation, it is important to ensure enough time for the magnetising current becomes to zero from its peak value. During the off time

$$t_{off-pk} = L_m \frac{I_{in-pk}(t)}{N V_{grid-pk}} \tag{3}$$

where "L_m" is the magnetising current, "$I_{in-pk}(t)$" is peak value of the input current, and "N" is the turns ratio of the transformer.

During the on time

$$V_{in} = L_m \frac{i_{in}(t)}{dt} \tag{4}$$

$$t_{on-pk} = L_m \frac{I_{in-pk}}{V_{in}} \tag{5}$$

$$t_{on-pk} = d_{pk} \frac{1}{f_s} \tag{6}$$

$$t_{off-pk} = \frac{V_{in} d_{pk}}{N V_{grid-pk} f_s} \tag{7}$$

where "V_{in}" is the input voltage, "d_{pk}" is the peak duty cycle, and "fs" is the switching current.

From the Eq. 7, it can be seen that in order to provide the converter operate in DCM mode the value of the d_{pk} and N should be adjusted. By using the Eq. 1 and the Eq. 7 can be rearranged as shown below

$$T_s - t_{on-pk} \geq \frac{V_{in} d_{pk}}{N V_{grid-pk} f_s} \tag{8}$$

By arranging the Eq. 8 d_{pk} and N can be calculated as shown below

$$d_{pk} \leq \frac{1}{\frac{V_{in}}{N V_{grid-pk}} + 1} \tag{9}$$

$$N \geq \frac{V_{in}}{V_{grid-pk}} \left(\frac{1}{d_{pk}} - 1\right)^{-1} \tag{10}$$

The value of the magnetising inductance is another important parameter in terms of storing sufficient energy to be fed to the grid. The transformer magnetising inductance can be calculated by using the following equation;

$$L_m = \frac{1}{2} \frac{\alpha^2 d_{pk}^2}{P_{rated} f_s} V_{grid-rms}^2 \tag{11}$$

$$\alpha = \frac{V_{in-min}}{V_{grid-pk}} \tag{12}$$

where "P_{rated}" is the rated power, "$V_{grid-rms}$" is rms value of the grid voltage.

Decoupling capacitor sizing is also important in terms of achieving an efficient MPPT operation (Hu et al., 2013). Due to being an operative interface between the PV panel and grid, the defined decoupling capacitor should cope with the instantaneous power mismatches. The capacitance of decoupling capacitor can be calculated by using the following equation;

$$C_D = \frac{P_{rated}}{2\pi f_{grid} V_{in} \Delta V} \tag{13}$$

where "C_D" is capacitance of the decoupling capacitor, "f_{grid}" is the grid frequency, and "ΔV" is the ripple on the voltage and should be below 5%.

Design Procedure for Single-Stage Flyback MI

When we consider the aforementioned advantages of single-stage flyback MI operating in DCM mode seems as an attractive solution for PV MI applications. It should be noted that the design procedure contains parameters related to each other (Mukherjee, 2013; Kavurucu, 2014). It is aimed to ensure the smallest volume for the defined rating power of inverter.

- By taking into account the Eq. 9 and Eq. 10, peak duty cycle and turns ratio of the transformer can be determined. It is crucial to provide that the flyback inverter operates in DCM mode. In view of this, required peak duty cycle and turns ratio values can be derived for different input voltage values.

- When operation in DCM mode is considered, the total conduction time should be less than the switching time period. By using Eq. 7, variation of conduction time with respect to turns ratio can be derived.
- "α" is another important parameter that needs to be determined, which directly affects the magnetising inductance of the transformer.
- Afterwards, the magnetising inductance of the transformer is determined.

Simulation Results

The validity of the investigated model is verified by constructing a PSCAD/EMTDC model with the following specifications;

- Input voltage = 29 V
- Input Current = 7.08 A
- Input Power = 205 W
- Open circuit voltage = 36.17 V
- Short circuit current = 7.5 A

The power circuit parameters are also given in Table 1.

Table 1. Power circuit parameters of the simulated model

Parameter	Values
Decoupling Capacitor	15.4 mF
Magnetizing Inductance	12.15 uH
Turns Ratio (N2/N1)	5
Switching Frequency	40 kHz
Bus Capacitor	400 nF
Filter Inductance (*Li - Lg*)	720 uH – 360 uH
Filter Capacitor (*Cf*)	880 nF
Damping Resistor	5 ohm
Grid Parameters	0.001 ohm – 15 uH

The simulated power circuit of the single-stage flyback MI, which consists of flyback converter, H-bridge unfolder, and output filter, is shown in Figure 8.

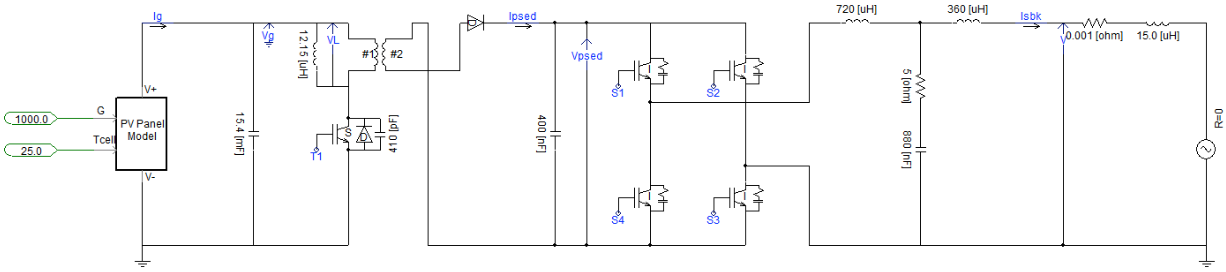


Figure 8. The simulated power circuit of the single-stage flyback MI

As it can be seen from Figure 9, PV output voltage oscillates around 29 V and with a current value of 7 A.

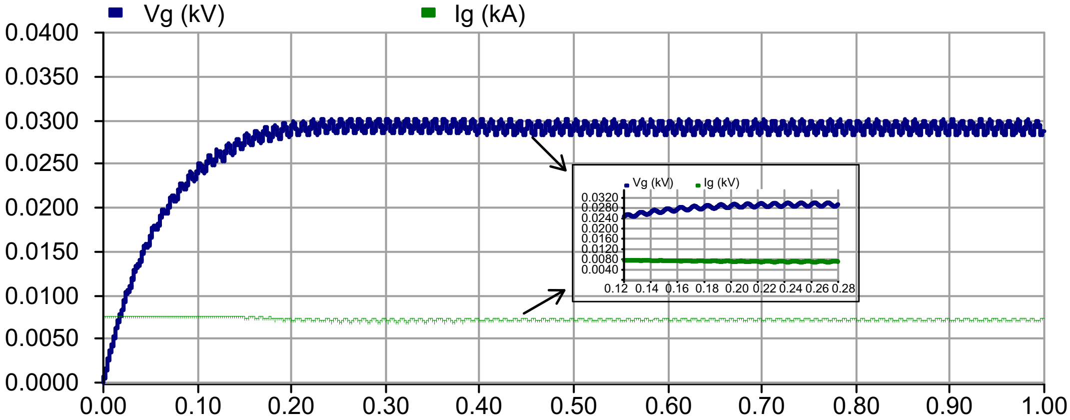


Figure 9. PV panel output voltage and current

In this study, perturb and observe (P&O) MPPT method is used for achieving the maximum power derivation from the PV panel. The output of the P&O MPPT block is used as a reference value in control block of single-stage flyback MI. In Figure 10, MPPT performance of the P&O method is shown. The reference value oscillates around 7.05 A.

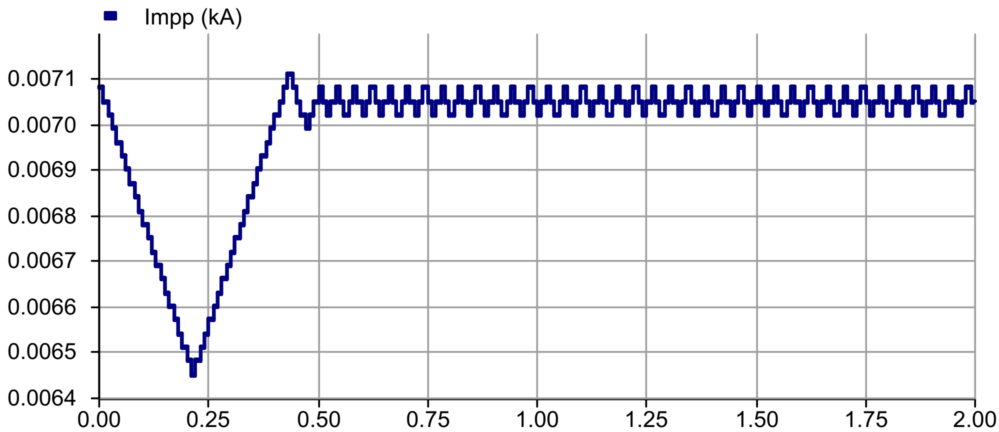
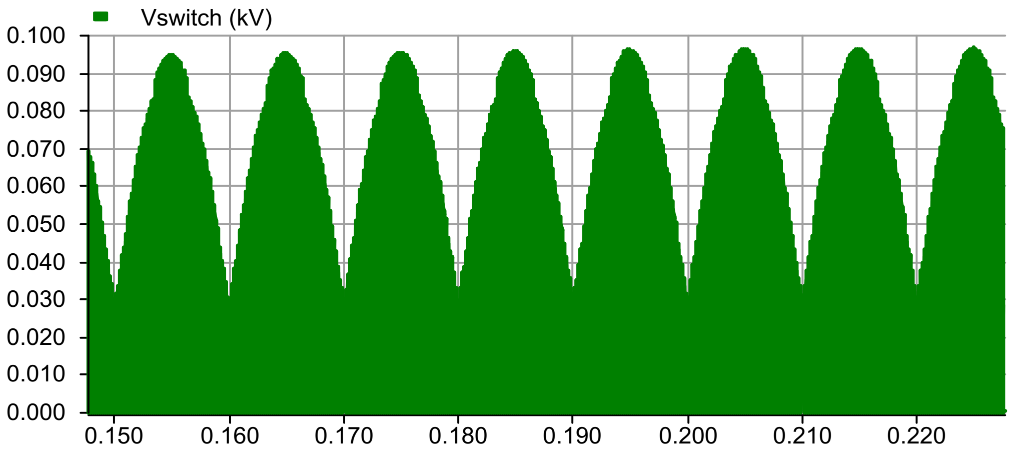
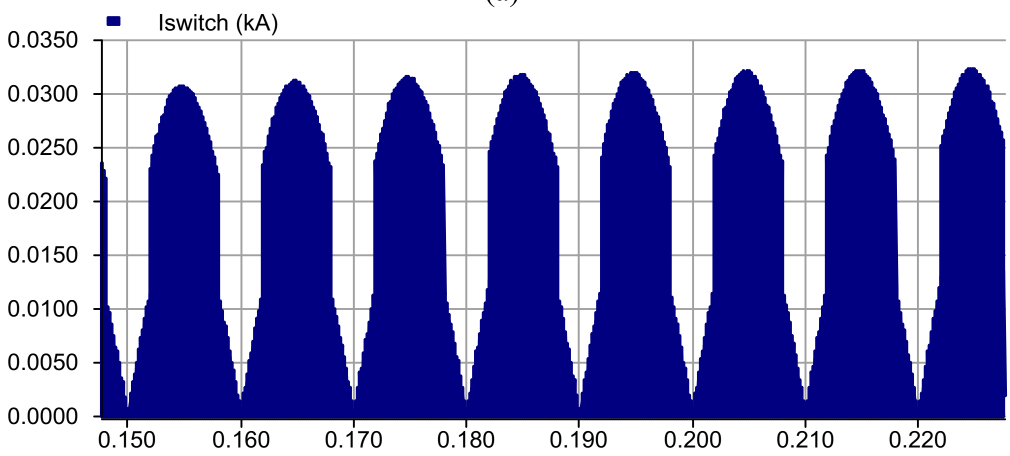


Figure 10. MPPT performance of the P&O method

In Figure 11, it can be seen from the switch current and switch voltage that the converter operates in DCM mode. The peak value of the current passing through the main switch reaches to 33 A and the peak value of the voltage across the main switch seems nearly 100 V.



(a)



(b)

Figure 11. (a) Voltage across the main switch (b) Current passing through the main switch

As it can be seen from Figure 12, rectified sinusoidal waveform on the pseudo DC-link capacitor fluctuates in duplicate of grid frequency. This rectified sinusoidal waveform is delivered to the network through the H-bridge unfolder stage and output LCL filter.

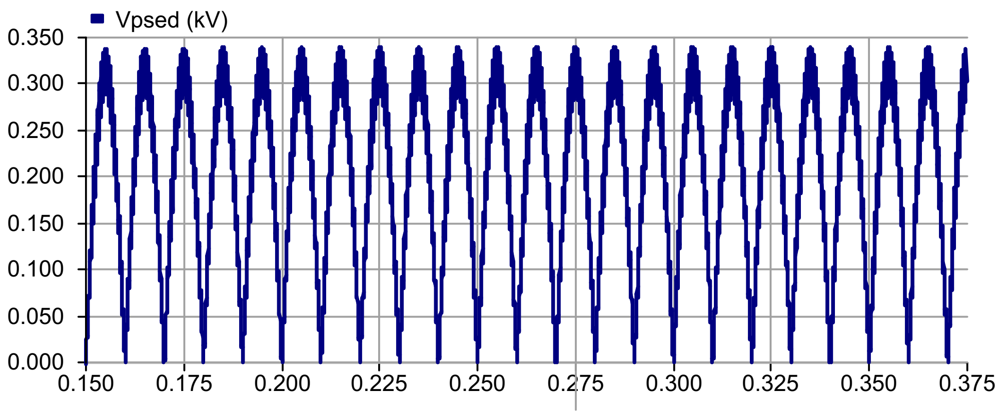
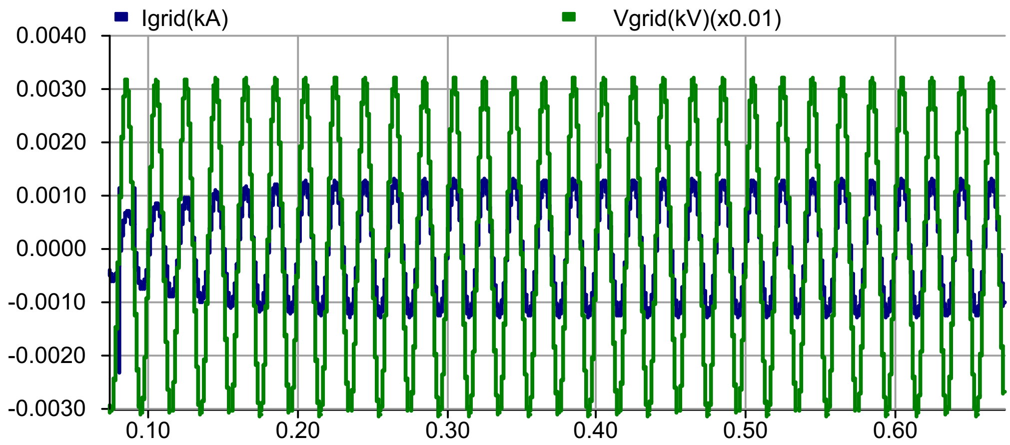
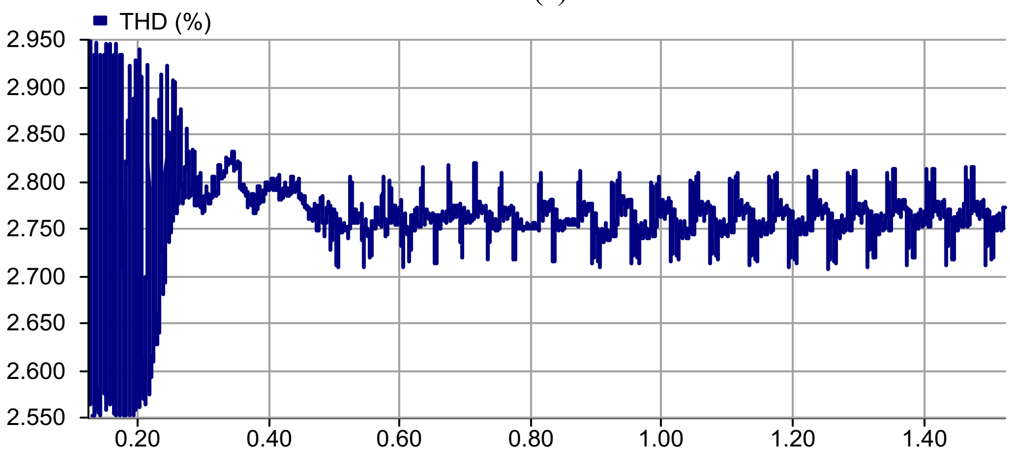


Figure 12. The rectified sinusoidal waveform across the bus capacitor

Figure 13 demonstrates the injected grid current for full load output of 180 W. Also the grid current harmonic is below 3%.



(a)



(b)

Figure 13. (a) Injected grid current (b) Grid current THD

Conclusions

In this paper, a rigorous model of single-stage flyback MI is simulated by using an electromagnetic transient software package PSCAD/EMTDC. A design procedure is highlighted for construction of an optimal single-stage flyback MI. The designing equations and controller structure are also provided. The system is analysed on a model designed 30V input PV voltage, 205 W maximum power rating, and 220 V_{rms}, 50 Hz utility grid voltage. The results demonstrate a close agreement with the design values. The simulation results show an efficiency of 91.9% for a 205W single-stage flyback inverter. From the results, it can be clearly said that single-stage flyback MI operated in DCM mode is a feasible solution for low power applications. In addition, simplicity of the controller structure related to utilisation of constant switching frequency and being easy to stabilise the control loop makes the system more attractive. The only drawback of the presented topology is its short lifespan due to the value of the decoupling capacitor.

Acknowledgements

This research study is supported by Scientific Research Project Unit of Cukurova University with the project number of FDK-2017-9136.

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