An improved control method to reduce harmonic level for a single phase grid-connected flyback micro-inverter of a small scale solar PV

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Abstract. One of an attractive solution for PV ac-module is flyback-type micro inverter since it has a number of advantages include simple control, stable current injection and potentially low-priced technique. But, it has high voltage ripple in the DC-link that may cause high harmonic distortion. Hence, a smooth DC voltage is required in order to maintain the total harmonic distortion within standard level. DC link voltage can be smoothened by using capacitor. However, the size of this capacitor is large and hence affects the weight and size of the inverter package. This paper proposes a control method to reduce harmonic level for flyback-type micro-inverter. MPPT (maximum power point tracker) technique used in this study is perturb & observe because it is the simplest online MPPT method with high efficiency. Several experiments are carried out to examine the effectiveness of the proposed method. The results show that the proposed method can reduce the harmonic level significantly and can be used as an alternative solution.

1. Introduction
A solar PV is characterized by a large degree of intermittency. Thus, for a standalone solar PV systems need large energy storage which typically has short lifetime and costly. For grid-connected solar PV systems, energy storage is not required and can give noteworthy cost reduction [1]. The main component of grid-connected solar PV is an inverter. There are various topologies of inverter that can be used to transfer power to the grid, i.e.: centralized and micro-inverter. When partial shading occurs, micro-inverter has better performance compared with that of centralized inverter since the micro-inverter is installed in every single PV module [2-6].

One interesting inverter topology is the flyback-based micro-inverter due to simple current control, the number of components is relatively low and potentially low in cost [7]. Flyback type micro-inverters are operated with discontinuous conditions (DCM) [8,9]. In DCM operations, the AC output current can be controlled without adding an AC output current sensor, because it operates as a voltage controlled current source [10,11]. Therefore, current sensors that are isolated and expensive on the secondary side are eliminated, resulting in a significant reduction in costs.

In most applications, micro-inverter is usually connected to a single phase distribution network. The power profile delivered from the inverter is time varying with 100 Hz of frequency for a 50 Hz grid
system. But, it should be noted that, the power at DC side of the inverter should be constant and it can be obtained by using parallel capacitor [3]. This capacitor is used as low pass filter to smooth the voltage.

To maximize the power extraction of a solar PV system, maximum power point tracker (MPPT) module is usually used. Various MPPT technologies have been proposed. The MPPT algorithm mostly uses a conventional method. It employs a modulated current in an open loop approach [12]. Besides, the conventional method is based on the assumption that the DC-link voltage is smooth. Thus, it will increase the Total Harmonic Distortion (THD) of the injected current [13-15]. Zengin proposes a new method so called Volt-second-based Control Method [16]. The purpose of his study is to reduce the THD resulted by the flyback-type micro-inverter. The control parameter employed is the magnitude of the modulated current. As a comparison, we propose a new method to optimize the power extraction and decrease the THD level by using phase control instead of magnitude control of the modulated current.

2. Flyback micro-inverter analysis

The circuit of a flyback micro-inverter is given by Figure 1. It comprises DC side switch (IGBT1) and two AC side switches (IGBT2 and IGBT3). Based on the polarity of the 50 Hz sinusoidal waveform, IGBT2 and IGBT3 work alternately. If the IGBT1 is on, then the current energizes the magnetizing inductance, \( L_n \). When IGBT1 is off, the energy stored in \( L_n \) is delivered to the grid via IGBT3 and D1 depending on \( t_{off} \) value. DCM occurs when \( t_{on} + t_{off} \) is less than the IGBT1’s switching period, \( T_f \). The highest ratio of the duty cycle \( (D_m) \) is given as follows:

\[
D_m < \frac{kV_{pg}}{kV_{pg} + V_{in}}
\]  (1)

where \( V_{pg} \) is peak voltage of the utility grid, \( V_{in} \) is the PV voltage and \( k \) is the turn ratio of the flyback transformer.

![Figure 1. Flyback-type micro-inverter circuit.](image)

One of the advantage of the flyback inverter is that the DCM operation may provide a simple open loop control without current sensor even though high peak current occurs at primary side of the inverter [8, 9]. But, if the DC voltage in the DC link fluctuates it will generate distortion on the output current and thus increase the harmonic level \( v_{in}(t) \). From Figure 1, if the IGBT1 is on then the magnetizing current, \( i_{in}(t) \), will increase linearly as given by the following formula:

\[
\frac{dI_{in}(t)}{dt} = \frac{V_{in}(t)}{L_n}
\]  (2)

The peak value of magnetizing current \( I_{n,peak}(t) \) is expressed as follows:

\[
I_{n,peak}(t) = \frac{V_{in}(t) \times t_{on}(t)}{L_n}
\]  (3)

If we modulate the duration of turn-on time with sinusoidal signal, the absolute value of the magnetizing current can be determined. The equation of duty ratio is expressed as follows:
where $D_n$ is the maximum value of duty ratio which is given by MPPT algorithm. $\omega$ is the grid frequency in rad/sec. Thus, the duration of turn-on time is

$$t_{on} = d(t) \times T_f$$

Substituting Equation (5) into (3), we can get

$$I_{n,peak}(t) = \frac{T_f v_{in}(t)d(t)}{L_n}$$

If IGBT1 is off, the magnetizing current is delivered to the secondary side of the HF transformer depending on the turns ratio, $k$. Hence, the secondary peak current is given as follows:

$$I_{d,peak}(t) = \frac{kT_f v_{in}(t)d(t)}{L_n}$$

The slope at the bottom as described by Figure 2(b) is determined by the following formula:

$$\frac{dI_{d}(t)}{dt} = -\frac{k^2 V_m(t)}{L_m}$$

It is assumed that the grid voltage, $v_{out}(t)$, is pure sinusoid and is given as follows:

$$v_{out}(t) = V_m \sin \omega t$$

$V_m$ is the amplitude of the grid voltage, $v_{out}(t)$. From Equation (7) to (9), the time required to reset the magnetizing current can be determined as follows:

$$t_{off}(t) = \frac{T_f v_{in}(t)d(t)}{kV_m \sin \omega t}$$

Based on Figure 2(b), the average value of low frequency AC current can be determined by averaging the triangle current waveform as given by the following Equation:

$$i_{out}(t) = \frac{1}{T_f} \times \frac{I_{d,peak}(t)I_{off}(t)}{2}$$

Substituting Equation (7) and (10) into (11), we get:

$$i_{out}(t) = \frac{T_f V_m^2(t)d^2(t)}{2V_mL_n \sin \omega t}$$
3. The proposed control method

Equation (12) depicts that the duty cycle and DC voltage at the PV side may influence the current delivered to the grid. Besides, the voltage at PV side can also affect the grid current. In the standard control techniques, the voltage at PV side is constant, and hence the duty cycle function $d(t)$ is modulated in order to get rectified sinusoidal current waveform. But, this condition may cause current distortion.

The control technique uses a duty phase shifter $\delta(t)$, which is the phase angle between $v_{out}(t)$ and $d(t)$. Hence, we can modify Equation (4) as follows:

$$d(t) = D_n \left| \sin \omega t \pm \delta(t) \right|$$

(13)

Substituting Equation (13) into (12), the current delivered to the grid can be found as follows:

$$i_{out}(t) = \frac{L}{2V_m} \frac{V^2_m(t)D^2_n \sin^2 (\omega t \pm \delta(t))}{L_n \sin \omega t}$$

(14)

The phase angle $\delta(t)$ is determined using algorithm as given by figure 3.

![Figure 3. Block diagram control for calculating duty multiplier.](image)

From Figure 3, we can determine $\delta(t)$ by using the following Equation:

$$\delta(t) = k(t) \left[ K_p + K_i \int dt + K_d \frac{d}{dt} \right]$$

(15)

$k(t)$ is the output value determined MPPT algorithm. In this paper, MPPT algorithm used is P&O technique. The proposed method is simulated using Matlab/Simulink. Figure 4 (a) shows the DC voltage at the solar PV output. Figure 4(b) is the response of duty ratio, $d(t)$ whereas Figure 4(c) depicts the PV current delivered to the grid.

![Figure 4. Waveform DC voltage at PV side, $D_t =$ Duty ratio $d(t)$, $I_{grid} =$ Grid current $i_{out}(t)$.](image)

4. Results and discussion

Figure 5 shows the investigated circuit including the proposed control design whereas Figure 6 depicts the conventional design as comparison. Several experiments are carried out to verify the effectiveness of the design and the circuit is modelled using Matlab/Simulink. The circuit parameter used in the simulation is shown by Table 1 and Figure 7 is the irradiance model used in the experiments. Figure 8 and 9 depict
the active and reactive power responses, respectively. These figures comply that the proposed method provide less reactive power than that of the conventional method. Hence, it can increase the power factor of the inverter operation. The THD profiles of the two control methods are given by Figure 10 and 11. The conventional method gives 6.13 % THD and the proposed method provides better THD profiles with 4.55 %.

![Figure 5. The flyback micro-inverter with the proposed control method.](image)

![Figure 6. The flyback micro-inverter with the conventional control method.](image)

| Table 1. Micro-inverter specifications. |
|----------------------------------------|
| Parameter      | Value                        |
| Voltage input  | 18 V (DC)                    |
| Voltage output | 220 Vrms                     |
| Frequency      | 50 Hz                        |
| Maximum Power  | 120 W                        |
| Switching frequency | 10 kHz          |
| Inductance Magnetizing | 3 mH                    |
| Filter L/C/L   | 0.28 mH/3uF/1 mH            |

![Figure 7. Solar irradiance.](image)

![Figure 8. Active power responses.](image)
5. Conclusion
An improved control method to reduce harmonic level for a single phase grid-connected flyback micro-inverter has been presented. To verify the effectiveness of the design, several experiments are performed and the results are compared with that the conventional method. The results show that the proposed method may increase the power factor and can reduce THD level from 6.13 % to 4.55 %.

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Figure 9. Reactive power responses.

Figure 10. THD of grid current for the conventional control method.

Figure 11. THD of grid current for the proposed control method.
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