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Published in:
Proceedings of 42nd Annual Conference of the IEEE Industrial Electronics Society

Link to article, DOI:
10.1109/IECON.2016.7793632

Publication date:
2016

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

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Grid-connected Photovoltaic Micro-inverter with New Hybrid Control LLC Resonant Converter

Abstract—A high-efficiency photovoltaic (PV) micro-inverter consisting of two power stages i.e. a LLC resonant converter with a new hybrid control scheme and a dc-ac inverter is proposed, studied and designed in this paper. In the first power stage, the new hybrid control combining pulse-frequency modulation (PFM) and phase-shift pulse-width modulation (PS-PWM) is employed on a full-bridge LLC dc-dc converter, in order to achieve high efficiency when PV output voltage varies in a wide range. Moreover, a maximum power point tracking (MPPT) method based on power perturbation is implemented in the dc-ac inverter. Therefore, the complexity of regulating LLC converter can be reduced effectively, and efficiency optimal design can be carried out through the proposed designing procedure for the resonant tank of LLC converter. Finally, a prototype of the proposed PV micro-inverter (PVMI) is developed with rated power of 250W and output voltage of 220VAC/50Hz. The experiment shows that the peak efficiency of the PVMI is 95.5%, where efficiency of LLC converter is up to 97.7%, and the MPPT accuracy is more than 99%. Thus the validity of the proposed system structure, design and control method is verified.

Keywords—Photovoltaic micro-inverter; LLC resonant converter; PFM; phase-shift PWM; MPPT

I. Introduction

Nowadays, the PV generation configurations can be classified into central-inverter structure, string-inverter structure and AC-module structure. The central- and string-inverter structures are used for medium- and high-power PV generation whereas the AC module inverters are connected with each PV panel, a so-called micro-inverter, having output power no more than 300W normally \(^{(1),(2)}\). Compared with the other two configurations, advantages like capability against partial shadow, flexibility, and convenience for enlarging capacity appear in AC module \(^{(3),(4)}\). And energy yield of the AC-module is also higher than that of the other two configurations because of its higher utilization of PV panel, although its PVMI has lower efficiency. In \(^{(5)}\) it is implied that the generated energy from AC module equipped with micro-inverter is 14% higher than that of centralized structure. But because the PVMI has low and wide-range input voltage, and using isolated topology, it will meet more challenge of achieving high efficiency and high step-up ratio \(^{(6),(9)}\).

A grid-connected PVMI with a new hybrid control LLC resonant converter is proposed in this paper in order to obtain both efficient conversion and high step-up ratio under wide-range input voltage. This paper is structured as follows. After this Introduction, Section II presents the proposed PVMI configuration, hybrid control method for LLC resonant converter, and MPPT implementation. Section III describes the design of key parameters and simulations. Section IV presents a prototype with rated power of 250W, which is able to adapt to the wide-range input voltage well. Finally the conclusion is given in Section V.

II. Configuration and control of PVMI

2.1 System configuration

The proposed PVMI is illustrated in Fig.1. The power circuit consists of two high-frequency power stages. The first power stage DC/DC converter uses full-bridge LLC resonant converter with voltage-doubler rectifier to boost the low and variable input PV voltage into high DC bus voltage, which is controlled with the new hybrid PFM and PS-PWM. The second power stage of a dc-ac inverter inverts the DC bus voltage into grid AC voltage, which is controlled with the dead-beat scheme \(^{(10)}\).

![Fig.1 System block diagram of PVMI](image)

In this PVMI, the perturb and observation method is adopted and applied to the second stage dc-ac inverter to
implement MPPT [7]. The high DC bus voltage, acting as output of full bridge LLC resonant converter, is maintained constant with the hybrid control by using PV panel voltage $V_{pv}$ and bus voltage $V_{bus}$. The reference of injected grid current is obtained via MPPT by using the grid root mean square (RMS) voltage $V_{grid}$, the injected grid RMS current $I_{grid}$, and $V_{pv}$. Moreover, anti-islanding protection can be also achieved by the phase-lock logic (PLL) and active frequency drift with positive feedback (AFPDF) [11]. The ac current with low total harmonic distortion (THD) is obtained through dead-beat control by using $V_{bus}$, grid instantaneous voltage $v_{grid}$, and inductor current $i_L$.

2.2 Hybrid control for full bridge LLC resonant converter

Zero voltage switching (ZVS) for the primary side switches and zero current switching (ZCS) for the secondary side diodes can be realized via resonance existing in LLC resonant converter. As shown in Fig. 2, vertical and horizontal axis represents the switching frequency $f_s$ and the phase-shift duty cycle $D$ respectively. Power can be converted efficiently under narrow-range input voltage with control I i.e. traditional PFM, where the voltage gain is only regulated with $f_s$ [6, 7]. Great challenges in magnetic components, system control, and system stability occur when applying control I to PV panels because of the wide-range switching frequency resulted from wide-range input voltage of PV panel and wide-range load variation. Efficient power conversion under wide-range input voltage can be realized through applying control II. As depicted in Fig.2, PFM is adopted in a region where $f_s$ is smaller than a specific value, while higher $f_s$ for regulation is needed, PS-PWM is used, and so $f_s$ range is limited. The efficiency, however, will decrease under PS-PWM on occasions of high input voltage or light load due to the large $D$ which tending to result in the increases of internal circumfluent current loss.

\[
M(f_s, D, k, Q) = \sin \frac{\theta_2}{2} \left( \frac{f_s}{f_{fr}} \right)^2 + \left( f_s - f_{fr} \right)^2 \frac{2}{1 - \cos (D \cdot \pi)}
\]

Where $D=1-D$, $k$=magnetizing inductance $L_m/L_r$, $Q$ is the quality factor of the resonant tank. The $M$ acts as the function of $f_s$ and $D$, $k$ and $Q$ are fixed with the constant parameters of the resonant tank. It is noted that the voltage gain $M$ in Equation (1) will be equal to that of traditional control I when $D=0$ i.e. no combining PS-PWM. So, the Equation (1) is also the $M$ expression for the PFM control mode via setting $D=0$.

The PFM control mode can be realized the same like that of traditional PFM. In order to get a specific voltage gain, there exists a variety of combinations $f_s$ and $D$ under PS-PWM+PFM mode. The combination guideline can be analyzed according to Equation (1). Because the PFM+PS-PWM control mode is introduced at $f_s > f_{fr}$, and at $f_s > f_i$, the voltage gain $M$ is less than 1, the following analysis will be only considered at $M<1$. Normalized switching frequency $f$ vs. $Q$ and $D$ at different $M$ is shown in Fig.3. Here defining $f=f_i/f_s$, and "$f>1$" means that the LLC converter operates under PS-PWM+PFM control mode. It is can be seen that,

1. $Af1<Af2$, which means the range of switching frequency is limited more effectively at small $M$. In other words, impact resulted from introduction of PS-PWM control on switching frequency is enhanced under high input voltage.

2. The effect of PS-PWM on limiting switching frequency will be weakened with the increases of $Q$. It means PFM control performs better than PS-PWM control under heavy loads.

Fig.3. $f$ vs. $Q$ and $D$ @ $k=3.7$ under PFM+PS-PWM mode

In order to overcome the drawbacks by adopting control methods I and II, here a new hybrid control (control III) for full bridge LLC resonant converter is proposed. In control III, there is two control mode. One is PFM control mode when $f_i \leq$ resonant frequency $f_r$, ($f_r$ is resonant frequency of the LLC converter resonant tank, and $f_r=1/2\pi \sqrt{L_r/C_r}$), the other is control mode of combining PFM and PS-PWM (PFM+PS-PWM) when $f_i > f_r$. Here the $f_i$ is selected as frequency for transition of the two control mode, and the converter $f_i$ is designed to be equal to $f_r$ at nominal input voltage and output load working condition. Because PFM is also introduced to combine PFM+PS-PWM for regulation, $D$ will be reduced. Then not only the frequency range is limited effectively in favor of magnetic components design, system control and EMC filtering etc., but also the circumfluent current loss can be decreased because of small $D$. The new hybrid control scheme can be realized easily with digital control.
Therefore, the combination guidelines of PS-PWM+PFM control mode is that introducing large weight for PS-PWM under high input voltage or light load, and large weight for PFM under relative high input voltage or heavy load. Large weight for PS-PWM means that the converter is regulated mainly by PS-PWM and mainly by PFM vice versa. This combination can achieve good trade-off range limitation of between switching frequency and $D$. 

The program flowchart of the hybrid control is shown in Fig.4, which is described step-by-step as following. The output voltage $V_{bus}$ of the LLC resonant converter is compared with the reference voltage in analog to digital (AD) interrupt; thus obtain error $V_{error}$. The converter will be controlled with PFM if the new calculated switching frequency $f_s$ through PI controller is smaller than resonant frequency $f_r$. If not, the PS-PWM+PFM control mode will be activated. Then a modification of phase-shift duty cycle $\Delta D$ can be calculated according to error range which equaling to the differences between $f_s$ and $f_r$. Finally, $f_s$ and $D$ will be updated by adding $\Delta D$ to a reference phase-shift duty cycle $D_{base}$ which had been pre-stored in the register.

![Fig.4 Program flowchart of LLC converter with hybrid control](image)

2.3 MPPT control

Maximum power point tracking (MPPT) is necessary due to the existence of the maximum output power point in PV panel. Method of perturb and observation, which is classified into the first-stage perturbation and the second-stage perturbation, has wide applications [6] on account of its simplicity and high tracking accuracy. Compared with only PFM or PS-PWM, the hybrid control LLC resonant converter has not only two operation mode, but also two control variables $f_s$ and $D$ under PS-PWM+PFM mode. In order to simplify MPPT control, Perturb and observation method is adopted and applied to the second stage dc-ac inverter to implement MPPT. So, the first power stage LLC resonant converter is only controlled to maintained constant output voltage $V_{bus}$. In order to avoid high sensing loss resulted from low voltage and high current output of PV panel, the perturbing power for MPPT is calculated from sensing grid $V_{grid}$ and $I_{grid}$ instead of PV output current.

III. Design of key parameters and simulation

3.1 Design of resonant tank of LLC converter

The resonant tank design of LLC resonant converter has impacts on voltage gain, switching losses, and magnetic losses. Minimizing loss is the objective of designing the resonant tank on basis of analyzing the effect of resonant tank parameters on voltage gain and losses. Switches’ conduction loss and turn-off loss together are predominated. They are determined by RMS current $I_{Qrms}$ and turn-off current $i_{Qoff}$. Respectively. Moreover, $I_{Qrms}$ can also be used to evaluate the magnetic losses.

As shown in Fig.5, $I_{Qrms}$ and $i_{Qoff}$ vs. $k$ and $Q$ in the LLC resonant converter operating PFM mode with $f=0.8$ are plotted, respectively. Here $I_{Qrms}$ and $i_{Qoff}$ are normalized as $I_{Qrms}*$ and $i_{Qoff}*$. It is shown that large $k$ and $Q$ will achieve small currents, then resulting in the low switches loss. And $M$ will be decreased with increasing of $k$ and $Q$, resulting in wider switching frequency range. Under PFM+PS-PWM mode, the currents behavior is the same like that of PFM mode. In contrast, its $M$ will be increased with increasing of $k$, as shown in Fig.6. That is to say, large $k$ will not result in wider switching frequency range. Therefore, in the design $k$ and $Q$ of resonant tank, only effect of $k$ and $Q$ on $M$ under PFM control mode is considered.

![Fig.5 $I_{Qrms}$, $i_{Qoff}$ vs. $k$ and $Q$ under PFM mode and $f=0.8$](image)

![Fig.6 $M$ vs. $k$ and $Q$ under PFM+PS-PWM mode](image)

The magnetizing current decreases effectively with larger $L_{bus}$, which is proportional to the multiplication of $k$ and $Q$, resulting in losses reduction in the resonant network. According to the above conclusion, rules which should be followed in design of the resonant tank are summarized as maximizing the multiplication of $k$ and $Q$ for minimizing losses in resonant network under meeting voltage gain.
Therefore, requirements in the design the LLC converter can be listed as following:

1. Requirements of voltage gain:

\[ M(f_{\text{min}}) \geq M_{\text{max}} \]  \hspace{1cm} (2)

\( M(f_{\text{min}}) \) represents the voltage gain at the minimum frequency \( f_{\text{min}} \), while \( M_{\text{max}} \) is the maximum voltage gain under the whole ranges of input voltage and load.

2. Input impedance of the LLC converter need to be inductive in order to operate primary side switches under ZVS. In other words, \( \text{Im}(Z_{\text{in}}) \) must be greater than zero, where \( Z_{\text{in}} \) represents the input impedance of the converter. Therefore,

\[
\omega L_r - \frac{1}{\omega C_r} + \frac{R_{\text{ac}}^2 \cdot \omega L_m}{R_{\text{dc}}^2 + (\omega L_m)^2} > 0
\]  \hspace{1cm} (3)

Frequency making the left term of Inequality (3) equal to zero is normalized to be termed as \( f_{\text{Im}_0} \), then an inductive \( Z_{\text{in}} \) can be obtained only when inequality (4) is satisfied.

\[ f_{\text{min}} > f_{\text{Im}_0} \]  \hspace{1cm} (4)

\( k \) and \( Q \), shown as overlapped parts in Fig.7, satisfies both Inequality (2) and (4). Then finding \( k \) and \( Q \) to maximize the multiplication of \( k \) and \( Q \) can achieve optimal design.

According the design procedure, key parameter is designed to be listed as follows for a PVMI prototype.

**PV panel voltage:** 22−45V/nominal voltage 31V;

**MPPT voltage:** 25−39V;

**PVMI output:** 250W /220V (+10%, -15%)/ 50Hz (±0.5Hz);

**The LLC resonant converter:**

- Output voltage or bus voltage \( V_{\text{bus}} = 380V \);
- Switching frequency \( f_s = 47k-110kHz \), and \( f_r = 65kHz \);
- Parameters of resonant tank:
  - \( k=3.7, \quad Q=0.48, \quad L_r=5.7\mu H \) (core size PQ32/25D, material TPW33), \( C_r=1.1\mu F, \quad L_m=21uH \), turns ratio of transformer: 7:44 (core size EER404513A, material TPW33);

The dc-ac inverter:

- Switching frequency: 40kHz for T3,T4; 50Hz for T1,T2;
- Inductance: \( L_1=L_2=2.5mH \) (core size PQ32/25D, material TPW33).

### 3.2 Modeling and simulation

Using the control scheme and design parameters, simulations of the PVMI are carried. Some key waveforms are shown in Fig.8. \( v_{gs}, v_{ds}, i_{D}, v_{Db}, v_{ab}, i_{Lr} \) represent drive signal of MOSFET, voltage across drain and source, current and voltage of rectifier diode, voltage across A and B in Fig.1, current of resonant inductor, respectively. It is can be seen that, the LLC converter operates with resonant frequency of 65.5 kHz at nominal input voltage 31V and full-load, while operates with PFM+PS-PWM mode, and \( f_r = 83.8 \) kHz, \( D=0.2 \) at input voltage of 39V and full-load. The switching frequency ranges from 47.3 kHz to 111 kHz. ZVS under full input voltage and loads. It should be noted that ZCS for the diodes, which is in favor of suppressing voltage spike, is also achieved even when \( f_r \) is higher than \( f_s \). The reason is that the diodes current lead because of phase shift. This ZCS behavior is greatly different with that under single PFM control. The simulation has good agreement with the design.

**Fig.8.** Key waveforms of LLC converter vs. input voltage

**4. Experimental results**

#### 4.1 Full-bridge LLC resonant converter

With the design parameters given in the “section 3.1”, the inverter prototype was constructed. Moreover the inverter Q1-Q4 selects Infineon BSC016N06NS and T1-T4 selects IPD60R600C6. And D1, D2 selects STTH5L06. The key waveforms of the full-bridge LLC resonant converter vs. input voltage are given in Fig.9. It is shown that the converter operates with \( f_s=f_r \) at nominal input voltage 31V and full load.
fs = 49.1kHz @ input voltage Vpv= 25V , output power Po=250W

fs =63.6kHz @ input voltage Vpv= 31V , output power Po=250W

fs =87.1kHz @ input voltage Vin= 39V , output power Po=250W

And the converter operates under PFM control mode when fs is lower than fr, while operates at PFM+PS-PWM control mode.

As shown in Fig.10, efficiency of the full bridge LLC converter is above 96% within MPPT voltage range from 25 to 39V and peak efficiency is high up to 97.7%.

Fig.9 Key waveform of full-bridge LLC converter vs. Vin

Fig.10 Efficiency of the LLC converter vs. Vpv and Po

4.2 PVMI prototype

The grid-connected current waveform and its THD, PF are given in Fig.11. The THD is equal to 1.5% at full-load, and equal to 2% at half-load. The efficiency is shown in Fig.12, and the peak efficiency is up to 95.5% at about half-load. The test shows that the prototype has good performance in injected current and efficiency. It should be noted that power consumption 1.45W of auxiliary power supply for the control and drive in the inverter was also included in the test, and this consumption takes up more than 1% of the half-load with peak-efficiency occurring.

Fig.11 Injected current @ Vpv=31V, vgrid=220Vac

The MPPT key waveforms are given in Fig.13. Under the test, the Regatron TCP.16.800.400.PV is used as PV simulator. The maximum power point is set to PMP=250W and VMP=36V. 

vPV, iPV, pPV is output voltage, current and power of the
simulator, and \( i_{\text{grid}} \) is the injected current of the inverter. The test shows that the inverter can search to the maximum power point quickly, and has good MPPT accuracy up to 99.3%.

Fig. 12 efficiency of the PVMI vs. \( V_{pv} @ v_{grid}=220\text{Vac} \)

![Efficiency vs Output Power](image)

Fig. 13 MPPT key waveform @ \( P_{m}=250\text{W}, V_{mp}=36\text{V} \)

![MPPT Key Waveform](image)

**V. Conclusion**

The PVMI will meet more challenge of achieving high efficiency because of wide-range input voltage. A PVMI with two high-frequency power stages is proposed, and the full bridge LLC resonant converter with hybrid control is used for the first power stage to meet PV wide range input voltage. The LLC resonant converter operates PFM mode when switching frequency is lower than the resonant frequency; otherwise, it operates with combining PFM and phase-shift PWM mode instead. Therefore, not only switching frequency range is limited, but also circumfluent current loss is decreased due to the reductions of phase-shift duty cycle under this proposed hybrid control. MPPT control is implemented on the second stage in order to avoid large amount of control variables existing in the LLC converter. Efficiency optimal design is implemented through the proposed design procedure for the resonant tank. Finally the experimental results verify the validity of the proposed scheme, design and control method.

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