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Topology, Efficiency, and Reliability

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An Overview of Photovoltaic Microinverters: Topology, Efficiency, and Reliability

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***Abstract*—This paper presents an overview of microinverters used in photovoltaic (PV) applications. Conventional PV string inverters cannot effectively track the optimum maximum power point (MPP) of the PV string due to the series configuration (especially, under partial shading conditions). In order to tackle this problem, microinverters make each PV panel operate at its own MPP so that the overall efficiency can be improved. In this paper, a detailed analysis is carried out among commercially-available microinverters in terms of topological structure and operational principle. Moreover, the latest products on the microinverter market and future trends of the microinverters are discussed in terms of efficiency and reliability.**

***Index Terms*—microinverter, PV application, flyback converter, DC-DC inverter, DC-AC inverter**

I. Introduction

Renewable energy systems have experienced a rapid development in last decades and the penetration level is still increasing due to the demand to reduce the fossil fuel consumption globally. Especially, the share of the solar PV capacity in newly installed renewable energy capacity was around 55% in 2017 [2]. In order to harvest the solar energy, a PV inverter is essential to transfer the extracted PV energy to the utility grid or load. Generally, the grid-connected inverters in PV systems can be classified into central inverters, string inverters and AC-module converters, also known as microinverters [3].

In the traditional PV applications with central or string inverters, all the PV modules are controlled by a single power converter. In this case, the overall performance of the system can be degraded significantly if one module in the shaded or faulty state. That is, the inverter cannot achieve the maximum power point tracking (MPPT) of each PV modules due to the series configuration. Moreover, the series connection of PV modules has a limited fault tolerance capability as the failure of one single PV module can cause the loss of power production of the entire PV string. To address this, the microinverter concept was introduced and it features low installation and maintenance costs, 'plug-and-play' operation, modularity and high efficient systems [4], [5]. In this configuration, each PV module is individually connected to a microinverter, and thus, the overall system efficiency and reliability may be improved by achieving the individual MPPT operation and eliminating the potential faulty condition [6], in particular, under partial shading conditions. The microinverters especially suitable for small-scale residential or commercial applications [7].

In general, the microinverter can be divided into two categories: single-stage and two-stage PV microinverter configurations. The single-stage microinverter is normally operated with the functions of boosting capability, MPPT, grid current control in single power conversion [8], [9]. Due to the high voltage boosting requirement of this application, the flyback converter is widely adopted in PV microinverters. For instance, as shown in Fig. 1, a single-stage microinverter is depicted, which includes a flyback inverter and a full-bridge unfolder to obtain the full sinusoid [1]. The main disadvantage of such a single-stage microinverter is that the double-line-frequency voltage ripples must be filtered at the PV-side. This requires large electrolytic capacitors (C_{pv}) at the PV side, which may be prone to failure under extreme conditions, e.g., high temperature [10]. Alternatively, the two-stage microinverters were developed in the literature, where the double-line-frequency voltage ripples can be buffered in the DC-link capacitor [11]. A two-stage microinverter has a step-up DC/DC inverter and a DC/AC converter to achieve the power injection. Although the two-stage microinverter can be separately optimized, the overall efficiency is decreasing due to the losses in both stages and the system cost is in general higher because of the high component count.

Recently, many efforts have been made to improve the performance of microinverters through topological innovations. Among others, the flyback-based microinverter, as shown in Fig. 1, is still one of the most widely used topologies as a single-stage configuration due to its simple control, low component counts and inherent galvanic isolation [12], [13]. Many attempts have also been made to improve the performance of the flyback microinverter by modifying the topology. For example, in order to recycle the leakage energy and achieve soft switching for the primary side active power devices, an active-clamped flyback converter with an unfolder was proposed in [12], as shown in Fig. 2. For two-stage topologies, the interleaved flyback converter and interleaved isolated boost converter are promising candidates as in the DC-DC stage [14], [15]. Furthermore, impedance source networks [16], [17] can also be adopted in microinverters. This is promising due to the attractive feature that the input voltage can be boosted during the shoot-through state. In [18] and [19], a high-performance quasi-Z-source series-resonant dc-dc converter was proposed as a promising topology for PV microinverters, which provides a wide input voltage and load regulation range thanks to the multi-mode operation.

Commercial products are also available on the market based

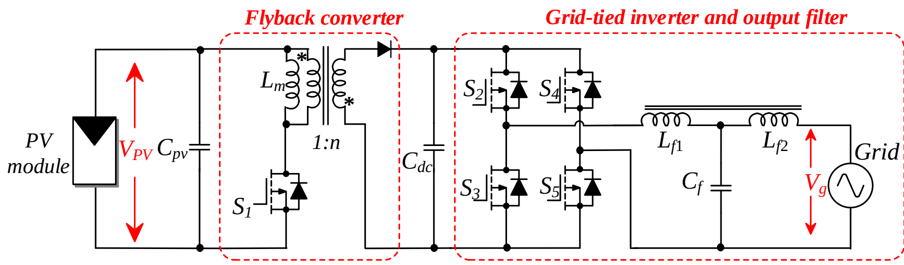

Fig. 1. Single-stage flyback microinverter [1], where L_m is the leakage inductance.

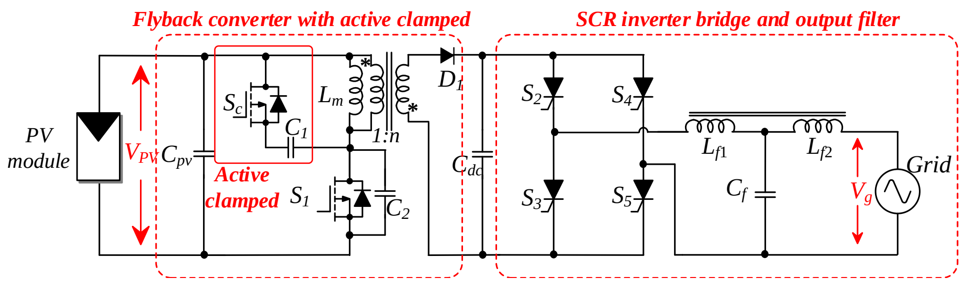

Fig. 2. Single-stage flyback microinverter with an active clamp circuit (SCR – Silicon-Controlled Rectifier) [12]

on the above topologies. The M250 microinverter is a representative product from Enphase Energy, which is based on the topology shown Fig. 1 [10]. In the past two years, Enphase has released the latest generation microinverter, Enphase IQ 7/7+ microinverter, which provides higher efficiency compared with the previous products [20]. Moreover, Texas Instruments (TI) also developed a two-stage PV microinverter using an active clamp flyback DC/DC converter with a secondary voltage multiplier and a DC/AC inverter [21]. In addition, ST Microelectronics launched a 250-W grid-connected microinverter [15], where an interleaved isolated DC/DC converter was employed.

Although certain microinverters have been extensively discussed in the literature, it still lacks a general benchmarking for the commercial microinverter products, especially, in terms of efficiency and reliability, which are the important performance metrics of microinverters. In this paper, the operation principles of the representative microinverter products for PV applications are presented in detail. Moreover, a detailed comparison among these products is discussed in terms of power rating, total harmonic distortion (THD), efficiency and reliability. Finally, it outlines the future directions to improve the performance of PV microinverters.

II. Operation Principles of the Selected Products

A. *Single-stage PV microinverter*

As shown in Fig. 3, the single-stage microinverter consists of two interleaved quasi-resonant flyback converter and a full-bridge unfolder. As discussed previously, the commercial product M250 from Enphase Energy is designed based on the topology shown in Fig. 1. Notably, it is a interleaved network which consists two flyback converters in parallel to meet the power requirements.

The flyback converter can be treated as a combination of a buck-boost converter and a high-frequency (HF) transformer with the turns-ratio being $1/n$. According to Fig. 1, when S_1 is ON, the primary side inductor is charged by the PV module, and the inductor current increases linearly. When S_1 is turned OFF, the stored energy in the primary-side inductor is delivered to grid/load side through the secondary side inductor. It should be noted that, normally, this system operates in the discontinuous conduction mode (DCM), where the losses can be reduced compared with the continuous conduction mode (CCM). Moreover, for the single-stage microinverter, the output voltage of the flyback converter is a rectified sinusoidal wave, which is also named a pseudo DC-link. The full-bridge inverter is then used to unfold the rectified voltage into a full sinusoidal voltage [22], [23] (i.e., operating at grid frequency).

Fig. 3. Photo of the Enphase microinverter M250 [10].

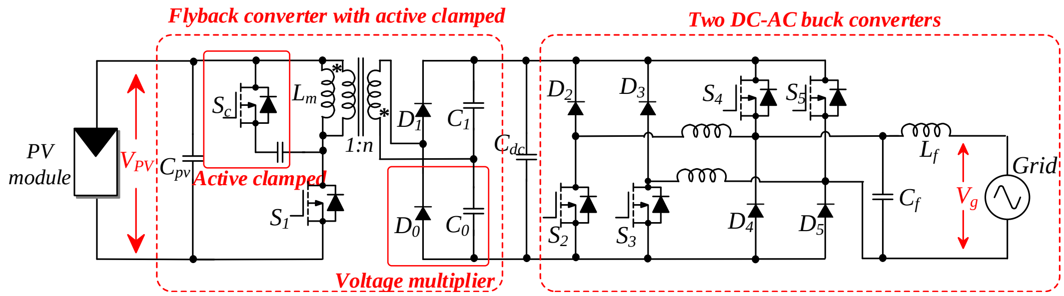

Fig. 4. TI's microinverter topology [21].

Fig. 5. Photo of TI's microinverter [21].

B. Two-stage PV microinverter

For two-stage PV microinverter products, they can be classified as flyback-based, isolated-boost-based and impedance-source based converters. Compared with the single-stage microinverter, it is clear that two-stage microinverter requires two power conversion stages, i.e., DC/DC and DC/AC. The DC/DC converter is used to achieve the MPPT and the DC/AC converter is used to convert the extracted DC power into the AC power and deliver it to the grid. The TI 280-W microinverter, as shown in Figs. 4 and 5, is based on an active-clamped interleaved flyback converter and a HF inverter. Compared with the converter in Fig. 1, the difference is that this DC-AC inverter operates at a high frequency while the converter in Fig. 1 only operates at the grid frequency (i.e., unfolding stage).

The operation principle of the TI's product can be summarized as following. First, the DC-DC active-clamped flyback converter draws the DC current from the PV panel and achieves the MPPT. Moreover, this flyback converter provides an HF isolation and the output voltage of the flyback converter is a high voltage. The inverter is then controlled to inject the output current into the grid.

The 250-W microinverter from ST Microelectronics is shown in Figs. 6 and 7, and it is based on two power conversion stages: an interleaved isolated boost DC-DC converter and a mixed frequency DC-AC converter [15]. The isolated boost converter has four operation modes. First, the switches $S_1$and S_2 are turned ON and the current flows through the inductors. In the second mode, the switch S_1 is still ON but S_2 is turned OFF. Then, the stored energy in L_2 is delivered to the secondary side so that the capacitor C_2 is charged. The third mode is the same as the first one. The last mode is contrary to the second mode, where S_1 is OFF and S_2 is turned ON, so the energy stored in L_1 is delivered to the secondary side. The DC/AC converter employs a hybrid modulation technique, where the power switches S_3 and S_4 operate at a high switching frequency, while the switches S_5 and S_6 only operate at the grid frequency. Moreover, the diodes D_3 and D_4 are used to inhibit the internal body diode, and the diodes D_5 and D_6 is used to overcome the potential problems when the MOSFET S_3 and S_4 turn on.

Figs. 8 and 9 show a quasi-Z-source (qZS)-based microinverter topology [18], [24] and its microinverter product is released as UBIK S350 OPTIVERTER. The qZS-microinverter includes a synchronous qZS network, a full-bridge inverter, a hybrid transformer with resonant inductors, a voltage doubler rectifier and a grid-tie inverter. This topology has the following features:

1) Compared with the traditional qZS inverter [25], the original input diode is replaced by a n-channel MOSFET, which can reduce the conduction losses.
2) A coupled inductor is implemented to replace the two discrete inductors in the traditional qZS network [25], which improves the power density and reduces the input current ripples.
3) External resonant tanks are not needed due to the fully integrated series-resonant tank, which lowers the volume and cost of the converter.

The operation of this topology can be divided into three modes: 1) normal mode, 2) buck mode, and 3) boost mode. In the normal mode, the MPP voltage of the PV module equals to the expected operating voltage and the operation principle in this mode is similar to that of conventional series-resonant converter at the resonant frequency. When the PV input voltage is higher than the expected, the converter operates in the buck mode. In this mode, the phase-shift modulation technique is used to control the output voltage. If the input voltage from the PV module is lower than the predefined value, this topology operates in the boost mode like a traditional qZS inverter and

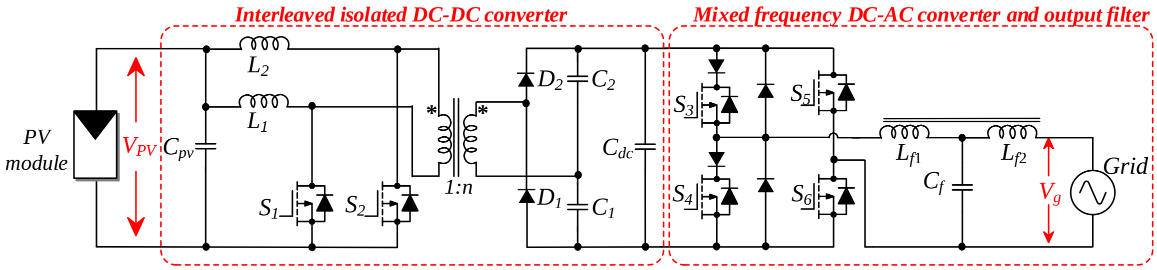

Fig. 6. The microinverter topology from ST Microelectronics [15].

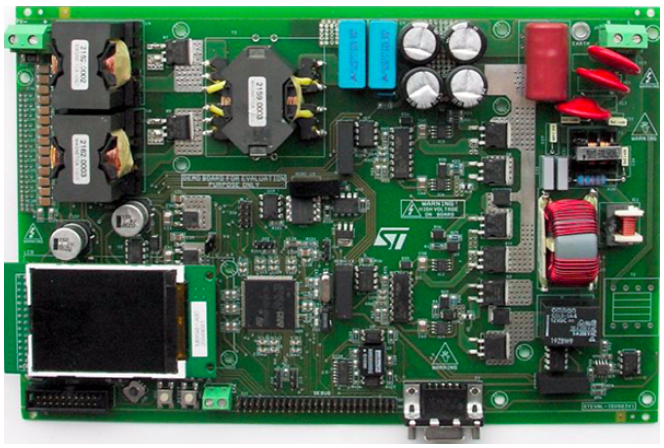

Fig. 7. Photo of the microinverter from ST Microelectronics [15].

the boosted voltage can be obtained by increasing the shoot-through duty ratio.

III. Comparison and Analysis of the Selected Microinverters

In order to benchmark the above four microinverters, a detailed comparison among these four topologies is carried out. The comparison of the above four topologies is summarized in Table I, where CEC stands for California Energy Commission.

Clearly, the selected four products are isolated PV microinverters, which can provide a galvanic isolation and a high voltage gain compared with non-isolated solutions. As it can be seen from Table I, the selected products power ratings from 250 W to 300 W, which match the power rating of typical PV module in the market. Moreover, it is observed that the Enphase M250 as a single-stage solution has the lowest total component count, which can lead to cost-saving. However, the main drawback of the M250, like most of the single-stage microinverters, is that a very large electrolytic decoupling capacitor is needed in order to filter out the double-line- frequency voltage ripples, as mentioned in Section I.

When only considering the number of active switches, it is interesting that although Enphase, TI and ST products have the same number of active switches, the power devices of the Enphase microinverter operating at a low frequency are more than the other products. Therefore, the efficiency and reliability of the Enphase converter is possibly higher than the TI and ST products, as indicated in Table I (the efficiency part). The switching technique is another consideration for microinverters. The TI, ST and UBIK products can achieve soft switching at the cost of extra component count by using the active-clamped circuit, as shown in Fig. 4 or the resonant tank as shown in Fig. 8, which in turn can decrease the high-frequency switching losses compared with the microinverters using the hard switching technique.

IV. Further Benchmarking and Future Trends of Microinverters

In addition to the above microinverters, Table II summarizes a survey of latest generation microinverters from the main-stream companies in terms of power rating, MPPT range, power factor (PF), THD, CEC efficiency, weight, power density and warranty. As presented in Table II, the power ratings of the microinverters range from 225 W to 320 W, and the efficiency and power density are up to 97.5 % and 6.85 $\text{W} \cdot \text{in}^{-3}$. In addition, compared with the previous generation of products, the warranty of current products is 25 years, which matches the lifetime of PV panels.

Although these latest microinverter products have good performance, there is room for further improvements of reliability and efficiency in future microinverter products. The future trends are listed as:

1) For single-stage microinverters, novel power decoupling schemes, as the replacement of the large electrolytic capacitor, are promising solutions to extend the lifespan of the microinverter.
2) The advanced wide-bandgap devices (e.g., gallium-nitride (GaN) and silicon-carbide (SiC) power devices) can achieve low power losses, which may compensate for the switching losses at very high switching frequencies. In that case, the challenges may become the design of electromagnetic interference (EMI) filters and the thermal management.
3) In the future, a microinverter may be integrated into a PV panel, which means that the microinverter should be occupy less space. Utilizing planar magnetic components and increasing switching frequency (e.g., 1 MHz) will become increasingly popular in order to increase the power density of the microinverters [24].

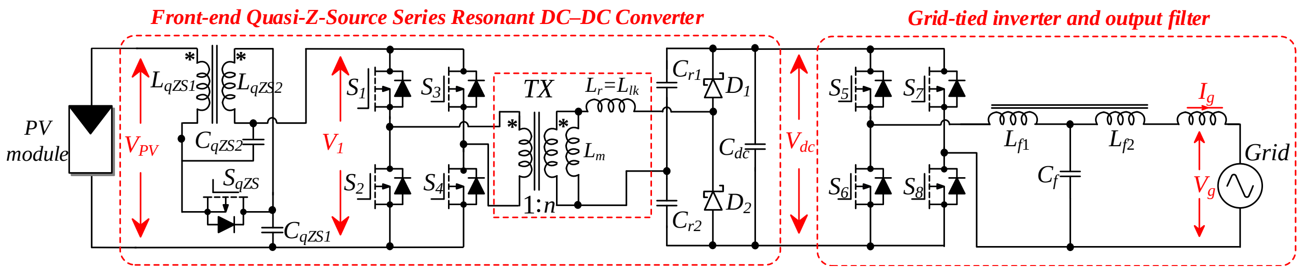

Fig. 8. Impedance-source-based PV microinverter topology [24].

TABLE I
COMPARISON OF SELECTED MICROINVERTERS.

Products	Power Rating (W)	Component Count							CEC Efficiency* Average Efficiency**
		Active Switch	High Frequency Active Switch	Low Frequency Active Switch	Magnetic Core	Copper Winding	Diode	Total	
Enphase M250	250	6	2	4	1	2	1	10	96.5%
TI Microinverter	280	6	4	2	3	4	6	19	92%
ST Microinverter	250	6	4	2	2	4	6	18	93.4%
UBIK S350	300	9	9	0	2	4	2	17	95%

TABLE II
COMPARISON OF SELECTED MICROINVERTERS.

Company	Model	Power Rating (W)	MPPT Range (V)	PF	THD	CEC Efficiency	Weight (kg)	Power Density ($W \cdot in^{-3}$)	Warranty (year)
Enphase	IQ 7X	320	25-79.5 V	0.85 leading to 0.85 lagging	-	97.5 %	1.08	4.68	25
Apsystems	YC600	600 (two module)	22-48	0.8 leading to 0.8 lagging	<3%	96.5 %	2.6	6.39	25
Chilicon Power	CP-250E	289	22-38.5	0.8 leading to 0.8 lagging	-	96 %	1.55	1.67	25
Envertech	EVT 300	300	24-42	>0.99	<3%	95 %	1.5	6.85	25
ReneSola	Replus-250A	225	22-55	>0.99	-	95 %	2	3.31	25
Darfon	G320	300	22-60	>0.99	<2%	96 %	1.3	2.83	25

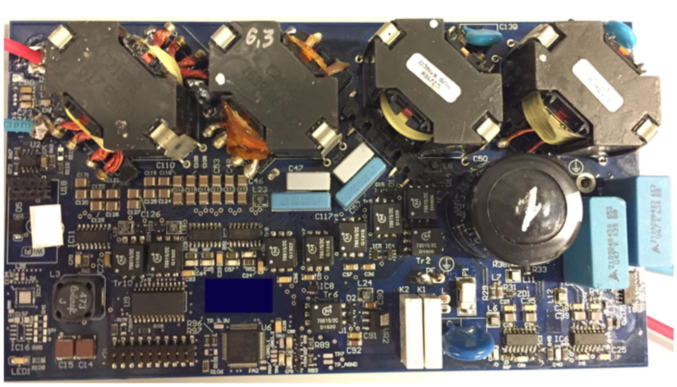

Fig. 9. Photo of the impedance-source-based PV microinverter topology [24].

V. CONCLUSION

In this paper, an overview of PV microinverters based on some selected mainstream products was presented. Through the analysis and comparison of the topological configuration and operation principles, the merits and drawbacks of these mainstream products were demonstrated. Based on the latest survey, the microinverters have superior performance in efficiency, power density and lifespan. Finally, to improve the reliability and efficiency, the future trends of microinverters are presented. Advanced power decoupling circuit and power semiconductor components will play a major role in the field of PV microinverters.

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