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Review and Comparison of Photovoltaic Single-Stage Micro-inverter Technologies in Residential Microgrids

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Abstract: This paper discusses the review of micro-inverter technologies in grid-connected photovoltaic systems with grid connection. Generally, single-phase micro inverters are classified into four topologies: 1) Single stage non-isolated, 2) Single stage isolated, 3) Double stage non-isolated, and 4) Double stage isolated. Here the single-stage isolated and non-isolated microinverter topologies are evaluated based on topology, efficiency, output power, THD, switching frequency, components count, and power decoupling techniques. It gives more insight into designing the future generation of single-stage PV micro-inverters.

***Index Terms* – Micro-inverter, Photovoltaic, Maximum Power Point Tracker (MPPT), Power decoupling**

1. INTRODUCTION

Future smart grid systems will feature the decentralization of power generation and distribution as a prominent characteristic. Diverse power generation sources will be deployed strategically in various locations, yet incorporated seamlessly into a unified grid network. Solar energy stands out as one of the most promising solutions for meeting the anticipated increase in energy demand. Photovoltaic (PV) panel installations can range from small-scale applications producing a few kilowatts to large-scale solar arrays producing several megawatts of energy. In addition to government incentives, the rising demand for renewable energy has accelerated the expansion of the solar energy market [1]. In accordance with the roadmap defined by the International Energy Agency (IEA), the contribution of solar energy to global electricity generation is projected to reach 16% by 2050 [2].

In any solar system, the inverter is a vital component that converts DC generated by solar panels into AC. Inverters can be classified according to power size as follows: Large-scale inverters, exceeding 100 kW; medium-sized inverters, between 10 and 100 kW; and small-sized inverters, less than 10 kW. The microinverter is a subcategory of the small-sized inverters. Microinverters are suitable for residential and commercial distributed generation. Micro inverters can be connected in parallel rather than in series [3]. In microinverters changing environmental conditions such as dust and detritus, shading, sub-optimal irradiance angles, and non-uniform temperatures have no effect on the whole array. One of the biggest advantages of micro-inverter circuits is to increase the size of a solar plant, you can simply add a single or any number of panels from different manufacturers and even different wattages in parallel to the existing system.

2. INVERTER FAMILIES

2.1 CENTRALIZED INVERTER

A centralized inverter is a power conditioning unit that communicates with a large number of grid-connected solar modules. PV modules are serially connected to form strings. All of these PV strings are parallelly connected to the inverter using string diodes. As depicted in Figure 1(a), the AC output is wired to the utility grid.

2.2 String inverter

Figure 1(b) depicts the string inverter, which is a miniature model of the centralized inverter. Each one of the PV strings is connected to a single string inverter in this configuration. The combined outputs of all inverters are then connected to the utility grid.

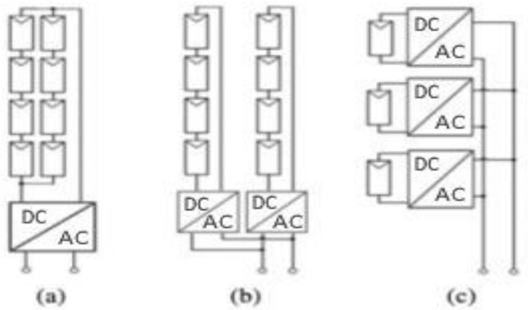

Fig -1: Inverter Architecture (a) Central (b) String (c) Microinverter

2.3 MICROINVERTER

The integration of a single PV module with a micro-inverter is depicted in Figure 1(c). Due to its modular design, this "plug-and-play" device provides the potential for simple expansion of the PV system.

3. MICROINVERTER TOPOLOGIES

According to the power conversion stages, micro-inverters are classified as single as well as double stage topologies. Then each one is subclassified as isolated and non-isolated topologies [4]. Topologies of single stage and double stage microinverters are illustrated in Fig 2.

Single-stage inverter topology has to perform boosting of voltage, MPPT, DC to AC conversion, and injection of AC current to the grid simultaneously in one stage. Its compact design with reduced power conversion stage and lesser number of components improves the power density of the system.

Table -1: Comparison of Grid Connected Inverters

Inverter Topology	Advantages	Disadvantages
Centralized inverter	Easy system design and implementation	Need DC cables with high-voltage between the inverter and PV modules
	Used for high power levels	Single MPPT for the entire PV system
	Low cost per Watt	mismatch losses between the solar modules
	Easy accessibility for maintenance and troubleshooting	string diodes cause losses
		nonflexible design
String Inverter	Smaller in size when compared to central inverters	Poor flexibility at partial shading cost per Watt is more than central-type inverters
	separate MPPTs can be applied to every string which increases the efficiency	
	Scalability for future expansion is possible with additional parallel strings	Higher per Watt cost than central inverter
	Short length of DC wires	
	String level monitoring is possible	
Microinverter	It provides plug-N-play operation and removes the need for DC switching points	High per watt cost
	As compared to the central and string inverters, it overcomes partial shading effects	
	Highest system flexibility for future expansion and life of micro inverters is more than traditional string inverters	They are exposed to the rack below each panel (hottest part of system) and could lead to problems
	MPPT at module level which improves energy harvest as compared to string inverters	

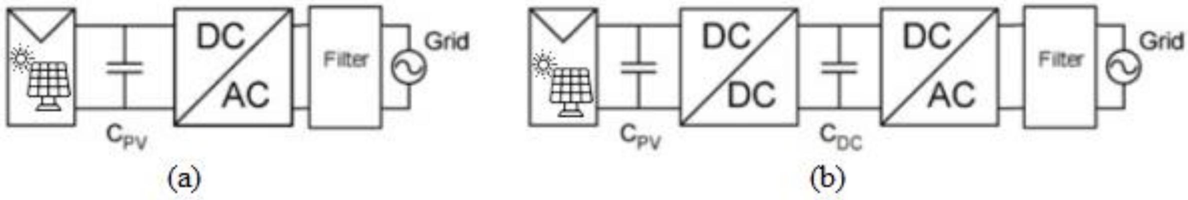

Fig -2: Inverter Topologies (a) Single Stage (b) Double Stage

In double stage topology, two stages are cascaded and the initial stage is MPPT controlled DC - DC step-up converter. And the next stage performs DC - AC conversion. Here higher numbers of components in double power processing stages lead to higher costs, significant power losses, and increased inverter size.

To manage the difference in power between the input-output of the microinverter, an electrolytic capacitor with high value is placed in parallel with solar modules. This large sized electrolytic capacitor will have a narrow lifespan and its performance is highly affected by temperature. This will degrade the performance of the PV inverter system.

Table 2: Comparison Table of Single and Double Stage Microinverters

Features	**Single Stage**	**Double Stage**
Efficiency	Highest	High
Reliability of Capacitor	Lower	Higher
Dc link capacitor	Electrolytic type	Thin Film type
Cost/unit	Moderate	Moderate
Total Reliability	Low	High
No of parts	Low	High
Flexibility	Low	High

3.1 SINGLE STAGE NON ISOLATED MICROINVERTER

3.1.1 Double Boost Topology

Cáceres [5] implemented two non isolated single stage boost converters in parallel. This converter produced a unipolar DC biased sinusoidal modulating waves of identical magnitude and frequency with 180º out of phase. To optimize inverter dynamics, sliding mode control was employed. This converter operated in continuous conduction mode and all the switches hard switched at high frequency with finite dead-time. It reduces its efficiency, even though the topology has simple structure. This type of design is used for the making of UPS systems and AC driver systems.

In [6], it is the modification of double boost inverter. Its performance can be improved by using the coupled inductor of the inverter. The generated output AC depends mainly on the duty cycle as well as the turn’s ratio. The duty ratio can be reduced according to the increase in the turn’s ratio. The presence of coupled inductor reduces the ripples in output voltage as well as input current. With high frequency switching, the volume of the microinverter can be considerably reduced. Each converter has a modulation of 180º which is out of phase with each other. Here, the load is distributed among the outputs of boost converter in a differential manner. Due to this, DC voltage difference between the load will be zero. The disadvantage of this type of micro-inverter is that it has a lower performance during partial shading because of the narrow MPP tracking range.

The reference [7] proposes a combination of a boost converter along with a full-bridge inverter. It uses two hysteretic controllers. The first one is used for the grid injected current while the second one is used for panel current. The major disadvantage here is large switching losses as well as high voltage stress across the DC link capacitor. The presence of single boost inductor eliminates the circulating currents.

Single-stage topology in [8] is combined version of boost converter along with a half bridge inverter. During each half cycle of the output voltage, one active switch is working at a higher frequency. Thus, switching losses can be decreased. It eliminates the distortion problem caused by zero crossover. This uses the PWM principle and the inverter is working in discontinuous conduction mode (DCM).

The topology presented in [9] is a boost converter in combination with a half bridge inverter and coupled inductors which are used to improve the output voltage gain of the inverter. The demerits are large switching losses as well as large voltage stress across the switching components.

Table 3: Comparison Table of Single and Double Stage Microinverters

Topology	Power (W)	Efficiency (%)	THD (%)	Output Voltage	Fs (kHz)	S	D	L	C2
ref [5]	500	…	4.74	127	30	4	…	2	2
ref [6]	260	97.5	3	220	50	4	…	2	2
ref [7]	200	90.5	…	115	25	4	2	2	2
ref [8]	100	90	2.68	110	100	4	3	2	3
ref [9]	200	89.3	4	110	50	4	3	2	3

S-no. of switches, D-no. of diodes, L-no.of inductors, C- no.of capacitors

Table 4: Summary of advantages and disadvantages of Single Stage Boost Topologies

Reference Literature	Features	Advantages	Disadvantages
[5]	Double boost converter differentially connected with 180^{o} out of phase	• simple configuration with four active switches • Use of 50% of duty cycle, makes gate driver circuit simpler	• Hard switching of all switches at high frequency with finite dead time, reduces efficiency • Voltage gain is reduced by its duty cycle • It has circulating currents and EMI problems
[6]	Double boost inverter along with coupled inductor	• Output voltage is based on the duty cycle as well as the turn's ratio of the coupled inductor, hence provides high voltage gain • Coupled inductor reduces output voltage ripple factor, input current ripple factor as well as volume, during high-frequency switching mode	• It provides low performance under partial shading • Hard switched switches with finite dead time, which reduces efficiency due to high switching losses. • It has circulating currents and EMI problems
[7]	Combination of boost converter with full bridge inverter	• It eliminates zero-crossover distortion problem • Single boost inductor eliminates circulating currents	• results large switching losses and large voltage stress • Complicated control scheme
[8]	Combination of boost converter as well as half bridge inverter	• A high frequency active switch is operated at every half cycle of the output voltage. Thus, switching losses can be decreased	• Hard switching and DCM mode create problems
[9]	Combination Boost converter as well as half bridge inverter with coupled inductors	• A pair of coupled inductors provide high voltage gain due to its turns ratio and thereby lowering the size of power decoupling filter	• large switching losses and large voltage stress in switching components

3.1.2 Buck Boost Topology

The paper [10] presents two buck boost converters; one operates at positive half cycle and the other at negative half cycle. Here two switches are operating at a higher switching frequency which reduces switching losses. Discontinuous conduction mode is used to obtain unity power factor with the grid. Switched inductors are used instead of inductors, which increases the gain of the converter. Thus, the voltage gain of the said inverter is improved by √2 times the gain in traditional buck boost converter.

Reference [11] presents active buck boost inverter that is an ideal combination for a wide range of inputs. The voltage boost of AC to AC, is made up of four active switches and avoids additional passive elements. Here DC to AC does the voltage buck conversion and the AC to AC stage performs the voltage boost function.

The topology in [12] proposes combined version of two single stage buck boost converters. A common terminal is shared between input as well as output ports to avoid the common mode leakage current.

The work in [13] proposes the working of Cuk derived microinverter in continuous conduction mode with common ground. This topology is suitable in standalone and grid connected modes with linear and nonlinear loads.

Table 5: Summary of Single Stage Non isolated Buck Boost Topologies

Topology	Power (W)	Efficiency (%)	THD (%)	Output Voltage	Fs (kHz)	S	D	L	C
ref [10]	85	87	…	220	10	4	8	3	2
ref [11]	500	96.5	…	100-200	20	8	…	1	1
ref [12]	300	95.7	4.3	110	50	4	…	3	3
ref [13]	300	94.5	4.55	…	50	5	…	2	3

S-no. of switches, D-no. of diodes, L-no.of inductors, C- no.of capacitors

Table 6: Summary of advantages and disadvantages of Single Stage Buck Boost Topologies

Reference Literature	Features	Advantages	Disadvantages
[10]	Single stage, non-isolated, Double buck-boost converters with interleaved inductors	• Switched inductors are used instead of inductors, which increases the gain of the converter to √2 times gain in traditional buck boost converter	• Adding 4 switches, 8 diodes, and 4 inductors makes this topology expensive
[11]	Buck boost inverter	• DC - AC as well as AC - AC conversion circuits use the inductor along with capacitor in the buck boost inverter, which helps to avoid adding extra passive elements and transformer to boost its voltage	• Increased switch count. The circuit requires a large inductor value since it is used continuous conduction mode (CCM)
[12]	Two buck boost converters	• Two buck boost converters shares same terminal for input as well as output ports that avoids common mode leakage current	• Undesirable resonance can develop in between the inverter filter capacitor and the grid impedance due to the distortion in crossover
[13]	Ćuk-Derived	• Ćuk derived PV microinverter operated in continuous conduction mode removes the common-mode ground leakage current	• It is hard to control than in DCM

3.2 SINGLE STAGE ISOLATED MICROINVERTER

3.2.1 Flyback Topology

N. Kasa in ref [14] put forward an idea of a flyback inverter. It uses a centre tapped secondary winding without DC current sensor for MPPT performance. PV module output power is calculated as the product of PV voltage as well as current. PV current can be measured with the help of an expensive DC current sensor. In this paper, PV current can be calculated from PV voltage with the help of using a digital signal processor (DSP) on a real time basis.

Conventional flyback single-stage micro-inverter as well as a decoupling circuit is derived in [15]. Single diode and single switch are integrated by the implementation of the power decoupling function. By this, the required power decoupling capacitance will be lowered. So, film capacitors are preferred than electrolytic capacitors. Only two switches are allowed to work at high frequency. Power decoupling capacitance also behaves as a snubber circuit for transformer leakage inductance, which eliminates conventional snubber circuits. But high voltage stress will be formed in components in the auxiliary circuit.

Literature [16] illustrates flyback topology in combination with switch S2 and additional primary transformer winding, which reults in power decoupling. It proposes film capacitor with longer life instead of an electrolytic capacitor. Power decoupling capacitor acts as snubber capacitor as well as energy storage element which recycles the leakage energy in the flyback transistor, so additional dissipative circuits are not required. However, this topology suffers from high switching losses among the primary switches. It also causes conduction losses among the diodes.

Topology implemented in [17], ZVS approach is used for single-phase grid connected flyback inverter. In place of the diode and power MOFET, bidirectional switches are used on the secondary side. This is to implement soft switching in the primary switch. Additionally, these bidirectional switches are turned on under zero voltage switching.

Table 7: Summary of Single Stage Flyback Topologies

Topology	Power (W)	Efficiency (%)	THD (%)	Output Voltage	Fs (kHz)	S	D	L	C2
ref [14]	300	89	…	100	9.6	3	2	1	2
ref [45]	100	90.2	1.9	110	50	4	4	1	3
ref [16]	100	90.6	1.7	110	50	4	5	1	3
ref [17]	250	94	…	…	27-65	5	…	1	3

S-no. of switches, D-no. of diodes, L-no.of inductors, C- no.of capacitors

Table 8: Summary of advantages and disadvantages of Single Stage Flyback Topologies

Reference Literature	Features	Advantages	Disadvantages
[14]	Flyback with midpoint secondary winding	• PV current can be calculated from PV voltage using of a digital signal processor (DSP) on real time basis for MPPT performance, thus avoid expensive DC current sensor	• Hard switching and high stress on switches
[15]	Flyback converter without Electrolytic Capacitors	• Film capacitors are recommended than electrolytic capacitors due to power decoupling function • Only two switches are operating at high frequency • Power decoupling capacitance also acts as a snubber circuit for transformer leakage inductance, which eliminates conventional snubber circuits	• High voltage stress in auxiliary circuit components
[16]	Flyback topology with power decoupling function	• Power decoupling circuit allows the use of a long-lifetime film capacitor instead of an electrolytic capacitor • Power decoupling capacitor is used for energy storage and snubber to recycle leakage energy in the flyback transistor, so additional dissipative circuits are not necessary	• Suffers from high switching losses in the primary switches and conduction losses in the diodes
[17]	Flyback inverter with bidirectional switches on secondary	• Bidirectional switches are used on the secondary side of the transformer instead of power MOSFET and diode to implement soft switching of the primary switch. Additionally, these bidirectional switches are turned on under ZVS	• More number of switching devices needed

4.CONCLUSION

This paper narrates various microinverter topologies and related issues. Several research works are going on in microinverter based systems today because of their design simplicity, easy plug and play usage, higher reliability, elimination of the effect of partial shading considerably, and maximum power extraction. This investigation aims to provide information on various microinverter topologies. In circumstances requiring electrical isolation, flyback-type configurations are advised. For applications where isolation is not essential, non-isolated topologies are preferable. The non isolated configurations offer the benefit of reduced bulk and cost due to the absence of transformers. As each microinverter is associated with a PV panel the lifetime of the microinverter must match the PV panel which is normally 25 years. Research and Development are going on to increase the life span, lower the cost per unit, and increase the efficiency of microinverters.

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