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A COMPARATIVE ANALYSIS OF GRID CONNECTED SOLAR PV SYSTEM USING DIFFERENT INVERTER TECHNOLOGIES

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Abstract

This paper presents a techno-economic comparison among three inverter technologies-based PV systems available in the market: string inverter, power optimizer and micro-inverter. Reliability, conversion efficiency, environmental impact and cost of a simulation-based test case 7.26 kW solar PV system for a residential property at longitude 41°28'22.6"N, Latitude 81°47'56.0"W are examined and differentiate using the three inverter technologies. The two scenarios are used to evaluate the performance of each configuration: partial shading and with no shade. The power optimizer and micro-inverter provide module-level MPPT which makes them more reliable and efficient with less conversion losses moreover; module-level monitoring can be performed in these two inverter configurations. A tabular comparison of energy harvested under partial shading and without shading and cost for three inverter technologies has been presented in the paper.

Keywords: *PV System, String Inverter, Power Optimizer, Microinverter and maximum power point tracking (MPPT)*

INTRODUCTION

Since 2000, global cumulative solar PV capacity has continuously increased. The figure increased by 632.4 gigawatts between 2000 and 2019. In 2019, the worldwide total sun based PV limit added up to 633.7 gigawatts, with 116.9 gigawatts of the latest PV limit introduced therein same year [1] makes it an integral part of the electrical energy.

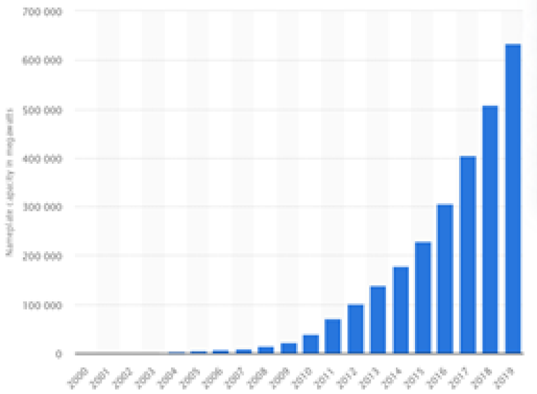

Fig.1: World Cumulative capacity of installed PV systems.

The use of PV modules upraise the necessity of energy alteration because the voltage provided by the module is direct current (DC) while alternating current (AC) is the current distribution network, thus the inverter must be used to perform this task. [2]The three basic configurations of inverters used in solar PV systems are (1) string inverter, (2) power optimizer and (3) microinverter. String inverters are old technology. They are a proven, durable, and cost-effective option that has been installed for decades over the world. Power optimizers and micro-inverters are the newer technologies and have been on the rise in popularity for the last couple of years, especially for the residential solar PV system, for their ability to improve the performance of the solar systems that are on complex roofs or experience shading.

It is important to note that power optimizers are not inverters, while micro-inverters are. This means that the best point-by-point comparison is between micro-inverters and a central inverter plus power optimizer system. However, the power losses due to shading and mismatch of the modules in the string inverter systems are well known, in this research we will focus specifically on the performance and economics of power optimizers and micro-inverters. Typically, most of the microinverter and power optimizers plus central inverter have 25 years of warranty that matches the warranty of solar PV modules. The high reliability and longer life of microinverter and power optimizer provide an additional benefit over the string inverter. [3] The inverters should have attractive qualities, for example, high performance, reliability, power density, low inverter and installation cost regardless of the PV system. [4]

The string inverter as indicated in Fig. 2(a); interface uses only one inverter for an entire PV array, to achieve an appropriate voltage level, a number of PV modules are linked in series to form an string and multiple strings are connected with inverter in parallel to increase the output power. The blocking diodes should be connected with each string to prevent the other strings from loading during partial shading.

With a simple architect and lower cost per watt, the string inverter configuration has a higher efficiency of up to 97 percent and is widely used in residential and commercial PV systems in a power range from 3 kW to 500 kW. However, this configuration has many drawbacks and limitations, such as there is only one MPPT stage in the entire string, resulting in low MPPT performance, the use of high voltage DC cables and the least versatile structure to benefit from large scale manufacturing. Moreover, the failure of the string inverter causes the complete system to be disrupted. [2]

Power optimizer PO with Central inverter Fig.2 (b), at a point where the output of PV module varies widely, i.e. due to shading, technological parameter mismatching, direction and angle variations for a small residential or commercial PV systems a PO is used. A power optimizer is a module-level micro-controller (DC to DC) that enhances the energy departure from the PV module through maximum power point tracking (MPPT) and synchronizes the output of each PV module with the string inverter input. Power Optimizer thus enhances the performance and efficiency of the PV system. In short, power losses are minimized and the PV system output is optimized by the methods described above.[5] PO provides 98.8% weighted efficiency with 99.5% peak efficiency.

Microinverters as shown in Fig. 2 (c) are inverters of a module-based type that have created a great deal of interest in recent years. The system's performance can be greatly enhanced by using this inverter due to their distributed architecture installed with individual PV modules. In addition, the module-based architecture of microinverter offers a range of advantages, such as low power losses, low converter power rating, minimum power losses, successful maximum power point tracking (MPPT) capability for PV module mismatch and partial shading. [6] Instead of DC, the use of AC cabling and connectors cuts construction costs and

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simplifies system architecture. Microinverter designs often allow for simplified wiring, resulting in lower installation costs. [7] For comparatively small structures with various roof designs and partial shading, this model is used. Because of the more versatile and module level configuration, the improvement in generation capacity depends on the customer's financial resources, is simpler than the power optimizer configuration. [2]

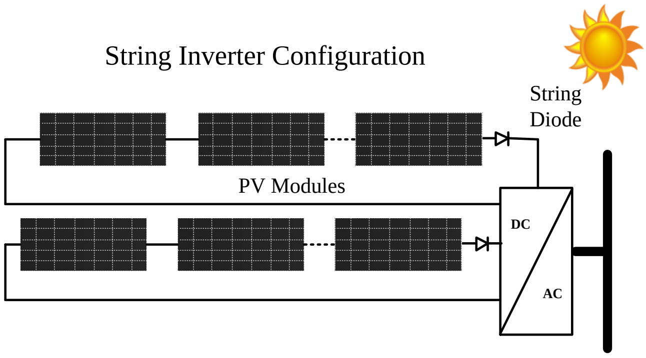

Fig.2 (a): String Inverter Configuration

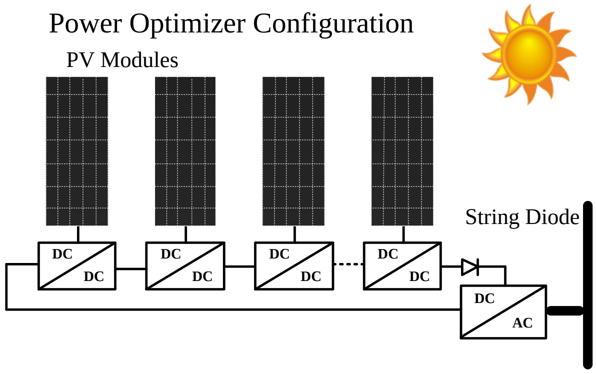

Fig.2 (b): Power Optimizer Configuration

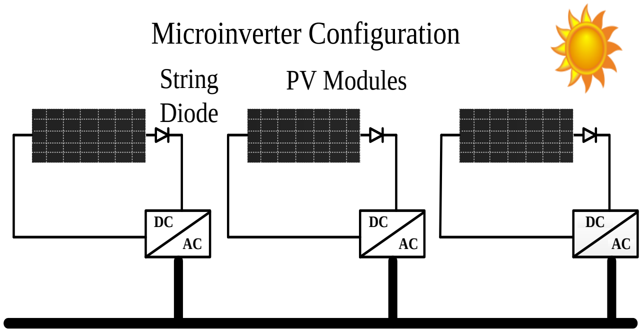

Fig.2 (c): Microinverter Configuration

CASE STUDY SYSTEM CHARACTERISTICS/ MODEL DEVELOPMENT

A 7.26 kW grid-connected PV system is built using three different inverter configurations using (1) partially shaded condition and (2) without shaded condition in order to provide a point-by-point comparison. A string inverter indicated in the first configuration Fig. 2 (a), with 22 solar PV modules of 330W each. Two parallel strings are generated and each comprising of 11 modules. Both strings are connected to a 7.0 kW inverter (SMA SB7.0-1SP-US). The second system consists of the power optimizer PO with Central inverter (SolarEdge SE7600H-US), with 22 solar PV modules along with power optimizers (P340) connected to each PV module as indicated in Fig.

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2(b). The third system Fig. 2 (c) is microinverter based configuration consists of 22 microinverter (Enphase IQ7Plus) connected on the back of each solar module and all microinverters are connected in parallel.The below table shows main component of the inverter configuration.

Configuration	PV Modules	Inverter	Optimizer
String Inverter	22 X Silfab 330W	Sunny Boy 7.0	N/A
Power Optimizer	22 X Silfab 330W	SolarEdge SE7600H-US	22 X P340
Microinverter	22 X Silfab 330W	Enphase IQ7 Plus	N/A

Table 1: Main components of inverter configurations.

This study evaluates the overall effect on the efficiency, life and total cost of the PV system with different inverter technologies. The maximum power point tracking (MPPT) function is available in all three inverters. In case of string inverter, MPPT is performed at string level to obtain maximum energy. In contrast, the solar power optimizer with central inverter and micro-inverter performs MPPT at the module level which improves energy generated and minimizes the partial shading impact. [7, 8] The power optimizers and micro-inverters are proposed mainly to overcome the energy losses due to partial shading. Moreover, they help to monitor the performance and identify any malfunction as it occurs, which speeds up the repair time. [3] String inverter provides the overall monitoring of the system while power optimizer and micro-inverter provide module level-monitoring. Consequently, it helps locating the fault.

RELIABILITY OF PV SYSTEM

String inverter manufacturers currently provide 10 years of warranty, whereas power optimizer system and micro-inverter manufacturers usually offer 25 years of warranty, so string inverter may be replaced at least once in 25 years of solar PV module warranty. [3] The most common failure equipment of the solar PV system is inverter. Two inverters must be part of the total system lifetime expense of the string inverter, the original and a substitute. Let's analyze the main component of any inverter: the Maximum Power Point Tracker (MPPT). Typically string inverters are consisting of two MPPTs. The modules of a system are split into two strings and connected to the inverter. As the intensity of the sun shifts during theday, the two MPPTs will constantly change the panel voltage and current to reach optimum power. The significant problem with string inverters is that a string of modules acts like old small string of lights: all the panels in the string are affected if one panel is affected by shade. The solution to this problem is offered by the power optimizer and microinverter configurations. They take the MPPT out from the inverter and place one MPPT (optimizer or microinverter) behind each module effectively. So, if one panel is shaded, the entire string output is not pulled down. [11]The easiest way to enhance electrical circuit reliability is to minimize the number of components in it. This is achieved in the configuration of the power optimizer by replacing a large number of individual components with a single proprietary application specific ICs (ASIC).The ASIC itself is manufactured using a fabrication process used for automotive electronics so that operating temperatures are well within spec and explicitly defined in compliance with proprietary design rules to allow the ASICs for a long 25-year lifetime. In order to ensure that the ASICpackaging is durable enough to withstand the mechanical and electro-chemical stresses faced during 25 years of everyday thermal cycling, extensive research and testing have been carried out. [12]

SIMULATIONS, RESULTS AND DISCUSSION

CASE 1: SOLAR ARRAY WITHOUT CONSIDERING SHADE ANALYSIS

A 7.26 kW of the solar array on a 30-degree tilted roof connected with string inverter (Sunny boy 7.0 kW) produces 8,298 kWh while with the same array SolarEdge inverter (SE7600H-US) with power optimizers (P340) connected with each module produces 8,571 kWh. When microinverter (Enphase IQ7Plus) are connected with each module of the arrays (where some modules are partially shaded), these inverters collectively produce 6,932 kWh as shown in the table below.

Annual Energy Production				
S. No	**Inverter Type**	**Without Shade**	**With Shade**	**Difference**
1	Power Optimizer with Central Inverter (SolarEdge)	8,571 kWh	7,609 kWh	11.89%
2	Microinverter (Enphase)	8,500 kWh	7,392 kWh	13.94 %
3	String Inverter (SMA)	8,298 kWh	6,932 kWh	17.94%

Table 2: Annual Energy Production

CASE 2: SOLAR ARRAY CONSIDERING PARTIAL SHADE ANALYSIS

In a shade of trees is considered the same arrays connected with string inverter (Sunny boy 7.0 kW) produces 7,392 kWh while it produces 7,609 kWh when connected with power optimizers (P340) and a central inverter (SolarEdge SE7600H-US). When microinverters (Enphase IQ7Plus) are connected with each module of the arrays (where some modules are partially shaded), these inverters collectively produce 6,932 kWh as shown in Table 2.

Microinverters connected with each solar module collectively produce more energy than conventionally used string inverter technology while power optimizers with central produce higher energy than both conventional string inverter and a microinverter when the shade of trees surrounding the property is not considered.

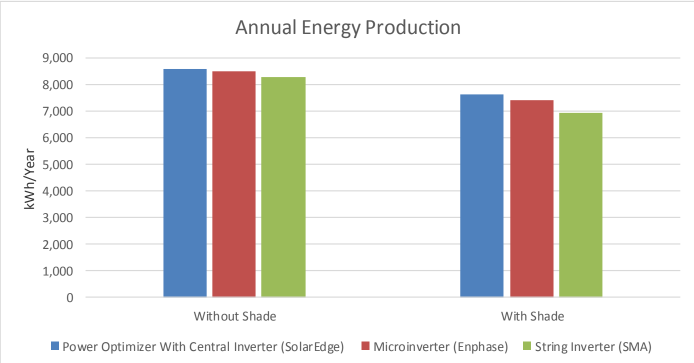

Fig. 3: Comparative annual energy production chart

It has been found that the shade of trees affects the production of the solar system with all inverters. However, it affects largely to the string inverter system. Thus, it can be seen from the obtained results that module level MPPTs improve the harvested energy in microinverter and power optimizer configurations.

ENVIRONMENTAL IMPACT

The factors influence the output of PV system is dust accumulation, birds' droppings, water drops, and partial shading. Partially shading condition (PSC) of PV system is examined in the section. Partial shading condition (PSC) in a photovoltaic system has been considered one of the most significant sources of losses. [15] Many MPPT based optimization techniques have been presented to increase the efficiency of PV device conversion. [17] The optimum solution is to avoid PSC wherever possible [16]. The impact of PSC depends on the area of the shadow on PV modules, reduction of solar irradiance, the presence of bypass diode and the inverter configuration.

COST

The PV system cost can be categorized mainly as

(1) electrical equipment,
(2) mechanical equipment,
(3) labor and
(4) repairs.

Besides the PV modules and mounting hardware cost, the other part of PV system cost varies depending on the inverters technology used. [3] Given the above factors, the String inverter, Power optimizer and micro-inverter configurations are evaluated. Although the cost of equipment makes up a large part of your quote for the PV system, the labor and permit costs is also taken into consideration. You would need to pay a fee to the utility company to connect your PV system to the grid. There are many people needed to bring your clean energy idea to reality, designing a project, site inspection, submitting permits and finally installation of PV system. [13] The installation of solar PV system requires highly skilled engineers for system design and installation labors as most of the municipalities in the US strictly follow NEC codes that lead to an increase in labor cost. The average cost of solar panels per watt can vary depending on the state in which you are installing, and it ranges from $2.40 to $3.22.[13]

To refine the cost estimation, the actual price without profit margin was obtained from an Ohio-based solar installer for all three inverter configurations. The below table 3 shows a brief cost comparison among three inverter configurations. The power optimizer and micro-inverter configurations have a little cost difference while string inverter has much lower cost than power optimizer and micro-inverter configurations.

String Inverter (SMA)			**Power Optimizer with Central inverter (SolarEdge)**			**Microinverter (Enphase)**		
Component	**Qty**	**Price in US $**	**Component**	**Qty**	**Price in US $**	**Component**	**Qty**	**Price in US $**
SILFAB SIL-330 W module	22	$4,704.48	SILFAB SIL-330 W module	22	$4,704.48	SILFAB SIL-330 W module	22	$4,704.48
SMA SB7.0-1SP-US inverter	1	$1,508.29	Power Optimizer P340	22	$1,514.83	Enphase IQ 7 Plus inverter	22	$3,387.65
Hial Solar Meter	1	$46.80	SolarEdge SE7600H-US Inverter	1	$1,741.35	Enphase IQ Combiner 80 A	1	$618.73
Miscellaneous Electrical Components	1	$364.00	Hial Solar Meter	1	$46.80	Hial Solar Meter	1	$46.80
Field Supplies - BOS	1	$1,300.00	Miscellaneous Electrical Components	1	$602.24	Miscellaneous Electrical Components	1	$589.74
Mounting Hardware with accessories	1	$1,742.67	Field Supplies – BOS	1	$1,300.00	Field Supplies - BOS	1	$1,300.00
Permit/IC	1	$700.00	Mounting Hardware with accessories	1	$1,760.27	Mounting Hardware with accessories	1	$1,760.27
Designs	1	$500	Designs	1	$500	Designs	1	$500
Labor	1	$2,225.00	Permit/IC	1	$700.00	Permit/IC	1	$700.00
			Labor	1	$2,225.00	Labor	1	$2,225.00
Total		**$13,091.24**	**Total**		**$15,094.97**	**Total**		**$15,832.67**

Table 3: Actual cost for different inverter configurations

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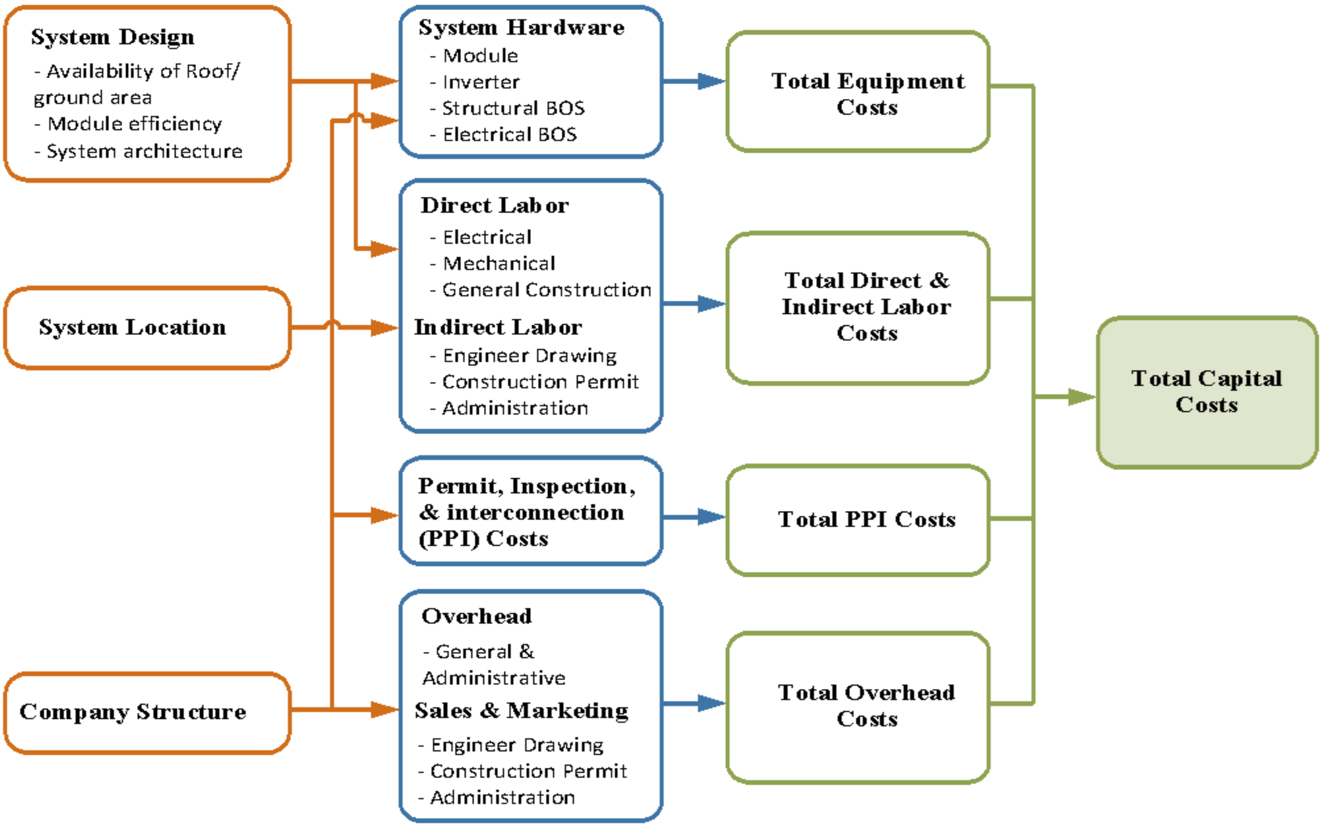

Fig. 4: Cost breakdown model of PV system.

CONCLUSION

A techno-economic comparison of three different inverter configurations of the PV system, string inverter, power optimizer and micro-inverter are presented. It includes reliability, availability, and cost and system production. The module level MPPT makes the power optimizer and micro-inverter (MI) configuration more efficient and reliable than string inverter. Further, it was concluded that these inverter configurations can be used for complex roofs such as multi-dimensional roof and/or partially shaded to get optimal energy. The lifetime of power optimizer and MI configurations are 15 years longer than string inverter however, the use of power electronic devices make their capital cost 14% and 19% greater than that of string inverter respectively.

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