BoS Cost Savings and LCOE Reduction for a 10 MW PV System with the 500 kW Transformerless Inverter

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Abstract—This paper presents the cost advantages that a high-performance, 500 kW, transformerless PV inverter can have for a solar PV system. Higher efficiency, smaller size, and lower installation costs impact balance-of-system (BoS) costs and reduce the levelized cost of energy (LCOE) compared with traditional, transformer-based PV inverters. These cost advantages should be considered as integrators and end-users in China and the U.S. select and install inverters in PV systems. This paper focuses on the effect of a more efficient PV inverter on BoS cost and LCOE, analyzing real PV grid-connected, transformerless inverter applications as well as unipolar and bipolar PV array configurations. Some standards and specifications for the PV inverters are introduced, such as CEC-weighted and EU efficiency. Using the Solar Advisory Model (SAM) and PVSYST software with PV module, inverter, and weather data, a simulation to calculate the LCOE and system performance rate of a bipolar PV array with a transformerless inverter is presented for a 10 MW PV system in Dunhuang, China.

Index Terms—Transformerless Inverter, CEC, Bipolar PV array, BoS, LCOE

I. INTRODUCTION

As photovoltaic module prices fall, the cost of PV inverters becomes more important. Traditional PV inverters must have isolation transformers, which increase the size and the cost of installation while reducing the overall efficiency. New transformerless PV inverter topologies offer the advantages of higher efficiency, smaller sizes, and lower installation costs to reduce overall system cost. Therefore, there is much interest in transformerless PV inverter technology.

Some basic functions are important for a grid-connected PV inverter, such as maximum power point tracking (MPPT) and anti-islanding. Much literature has been written on the benefits of transformerless inverters and the difficulties of isolation and common current [1]-[3]; however, information about BoS cost savings and LCOE reduction is limited. This paper focuses on the effects a true, transformerless inverter has on BoS cost savings and LCOE reduction.

Transformerless inverters offer higher efficiency over transformer-based inverters for residential applications in Europe [4]. Figure 1 shows the one kind of transformerless Grid Tie PV inverter has highest efficiency not only in

residential applications but also in commercial or utility applications in the U.S.

Fig. 1. CEC-weighted efficiency of inverters as a function of output power in North America [5].

A true, transformerless inverter has been defined as one that does not need a special transformer. The MV transformer is not the part of LC filter, so the inverter can work with a standard MV transformer to reduce the cost around 20%-30% compared to transformers specified by some inverter manufacturers.

II. KEY FACTORS FOR COST REDUCTION IN A PV SYSTEM

A. Higher-quality PV inverter with higher efficiency

A higher-quality inverter has been defined to incorporate higher energy efficiency (accounting for rated efficiencies as well as cooling energy losses used to generate more energy), wider operating temperature ranges to ensure the inverter performs well in summer and winter without power derating, lower BoS costs, and lower LCOE.

There are two kinds of weighted efficiency for PV inverters as shown in Table 1. Equation 1 shows the method for calculating the weighted efficiency. CEC efficiency has been used in the U.S., and it has more detailed information for test procedures and test results [6].

TABLE I
WEIGHTING FACTORS FOR CALCULATIONG WEIGHTED EFFICIENCY

Power Level	Factor	Weighting Factor	
		CEC	EU
5%	F1	0.00	0.03
10%	F2	0.04	0.06
20%	F3	0.05	0.13
30%	F4	0.12	0.1
50%	F5	0.21	0.48
75%	F6	0.53	0.00
100%	F7	0.05	0.2

$$\eta = F_1\eta_5 + F_2\eta_{10} + F_3\eta_{20} + F_4\eta_{30} + F_5\eta_{50} + F_6\eta_{75} + F_7\eta_{100}. \quad (1)$$

Where

$\eta_5, \eta_{10}, \eta_{20}, \eta_{30}$, etc. are the measured efficiency values at 5%, 10%, 20%, recorded in Table 1.

F_1, F_2, F_3, F_4 , etc. are the weighting factors defined.

Higher efficiency PV inverters offer the benefit of higher output power or fewer number of PV modules. It is important that the PV inverter has high efficiency at light loads to enable the PV inverter to turn on earlier in the morning and stay on later in the evening. However, most traditional inverters do not operate this way due to higher loss at light loading. A master/slave system can switch the output of a PV array to a single inverter to get higher output because the efficiency is better when loading greater than 20%.

Although this method may increase the performance rate of a PV system, it also increases the complexity and cost for parallel connection and control. Another disadvantage for M/S control is the circulation problem around the circuit of parallel PV array connection and parallel AC output it also reduces the output energy and makes the system unsteady [7]. The operation range of temperature between -35°C and 50°C is a necessity to ensure the inverter can work well in the northwest region of China. Table 2 shows a comparison for a high-quality, true, transformerless inverter with traditional inverters [8]-[11].

B. BoS Cost Reduction

Excluding PV modules and grid connection selection, balance-of-System (BoS) costs encompass all equipment, materials, and labor associated with the PV system as shown in Figure 2. Examples include the mounting, combiner box, DC and AC wiring, junction box, monitor system, surge protection system, and PV inverters. Today, due to the falling prices of PV modules, BoS costs are becoming a more important factor, giving solar businesses that can reduce BoS a competitive advantage [12]. Historically, BoS costs were considered to be fixed. However, optimizing the system design with a better PV inverter can significantly reduce BoS costs.

Some transformerless inverters with higher input voltage ranges (e.g., 660 V to 1200 V) reduce DC current 30% to 50% compared to traditional inverters. The lower DC current has the benefit of lower cable cost, lower labor for the installation, and lower DC and AC disconnect switch and

junction box costs. These inverters can be connected in parallel to a large, standard MV transformer to reduce custom MV transformer costs (up to 48%) [13] and increase efficiency. Larger MV transformers may be as much as 0.5 to 1% more efficient than smaller ones. Finally, outdoor inverter installations eliminate the cost of an enclosure to protection the inverter, and no external energy is needed for cooling the enclosure.

TABLE II
PARAMETERS FOR EU VERSIONS OF MAJOR PV INVERTERS

Item	AE Solaron® Inverter	Competitor Sx	Competitor Xx	Competitor SMx
AC Power	500 kW	500 kW	500 kW	500 kW
M/S Control	No need	No need	Option	Yes
SW Frequency	>18 kHz	<10 kHz	<10 kHz	<10 kHz
Temp Range ($^{\circ}\text{C}$)	-35 to 50	-20 to 50	-10 to 45	-20 to 50
CEC Efficiency (%)	97.5	96 with transformer	96 with transformer	97
EU Efficiency (%)	98.1	97	97.6	98.4
Efficiency (Includes Aux Power)	Yes	Yes	Need cooling energy	Without 2900W for Aux power
MPPT Voltage Current	660 to 1100 V 750 A	420 to 850 V 1228 A	450 to 800 V 1120 A	450 to 820 V 1200 A
AC Voltage/Current	480 V 630 A	265 V 1090 A	315 V 920 A	270 V 1070 A
Cooling Design	Liquid-Air	Air	Air	Air

Fig. 2. BoS system

C. Lower LCOE

In the past, dollars per Watt was an index used to estimate the cost of a solar PV system. It is easy to achieve low costs by using low-priced equipment. However, the dollar-per-Watt method does not consider the effects of lifetime and performance of the solar equipment such as the inverter and PV modules for the overall system. [4]. In the U.S., the Department of Energy (DOE) has chosen leveled cost of energy (LCOE) as a key performance parameter for

solar energy. LCOE reflects all aspects of the lifecycle cost of a PV system such as:

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}} \quad (2)$$

Equation 2 can be disaggregated for the solar PV generation as (3), which includes the installation, operating and maintenance costs, system performance, and reliability of equipment.

$$\text{LCOE} = \frac{\sum_{n=0}^N \frac{C_n}{(1+d)^n}}{\sum_{n=1}^N \frac{Q_n}{(1+d)^n}} \quad (3)$$

where

C_n represents costs such as installation, module, BoS, inverter, finance, and O&M in Year n , $n=0$ is the cost in year 0, equivalent to the capital cost.

Q_n is the electric energy produced by the system in year n . N is the project lifetime, and d is the discount rate.

Some major parameters increase the total lifetime energy production based on a higher-quality inverter such as wider temperature range, higher system performance, higher inverter efficiency, and higher system uptime. A higher-quality inverter will also reduce BoS costs with better designs and O&M cost reductions due to higher reliability.

III. MODELING OF SAM MODEL FOR A PV SYSTEM

A. SAM Model

To standardize the calculation of LCOE, the DOE commissioned the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories to develop the Solar Advisor Model (SAM) [14]. The SAM model includes PV module data, inverter data, and weather information per hour in a U.S. It can be used to calculate, analyze, and optimize the LCOE for PV projects in the U.S. [15].

The following is a list of the assumptions used in developing the mathematical LCOE model for this paper:

1. 10 MW PV project at Dunhuang, China
2. Finance model:
Inflation rate=2.5%, Inverter cost=0.25 USD/W
Module cost=1.8 USD/W, Debt Fraction=40%
Total Installation cost= 4.08 USD/W
3. 30 Years PV system lifetime
4. PV Module: Suntech 280-24-Vb-1
5. Inverters: AE Solaron 500 kW, Competitor Sx 500 kW, Xx 500 kW, SMx 500 kW

B. PV Module Information

Table 3 shows information for a Suntech 280 W PV module with temperature coefficients. It is very important to calculate the maximum open voltage at the lowest daytime

temperature condition and the short current at the highest temperature condition. Refer to the weather information of the PV project.

TABLE III
SUNTECH 280W PV MODULE INFORMATION

Module Information		Temperature Coefficient	
Model Number	STP280-24/Vb-1		
Maximum Power at STC	280 W	Pmp	-0.47±0.05 %/°C
Voc (V)	44.8 V	Voc	-0.34±0.01 %/°C
Isc (A)	8.33 A	Isc	0.055±0.01 %/°C
Vmp (V)	35.2 V		
Imp (A)	7.95 A		

C. PV Inverter Information

For this model, it is imperative to include the real efficiency of the PV inverter. Therefore, if an inverter requires an isolation transformer, then the efficiency is ~2 to 4% less when the transformer is added. System integrators and end-users often overlook the effect of inverter cooling energy. Keep in mind, however, that some efficiency is lost in configurations with air-conditioned enclosures to ensure maximum power output during the summer and at peak times. Almost all PV inverters employ air-cooled designs. If a 500 kW inverter has a power conversion efficiency of 97%, the balance of 15 kW of power is used for heat removal from the enclosure. Forced-air cooling systems in a typical 500 kW enclosure are designed so that fans lower the air temperature from outside of the enclosure through rain-proof openings, and the cooling fans remove heat away from temperature-sensitive components such as the IGBT or line filter inductor.

Air conditioner solutions can keep the temperatures low enough to make sure the inverters can output full power. However, they also expend extra energy for cooling, affecting the real efficiency of the inverter. Figure 3 compares two 500 kW PV inverters based on their CEC efficiency record. The difference between the green curve and the blue curve is small but extends to 3-4 % with a transformer. And the EU efficiency downs about 0.5-2 % if the cooling energy (Fans and air condition) and Aux power are considered [11]. The above problem does not occur with liquid-cooled designs that eliminate auxiliary energy for cooling.

NREL defines the new 500 kW PV inverter includes the advanced and high-reliability function in 2008 [13]. The subcontract report also defines the specification for high input voltage of 1000 VDC with bipolar PV array design. Bipolar PV arrays offer the benefit of higher input voltage and lower input current. This causes lower cable power losses and costs but also meets the NEC limits under 600 VDC.

Fig. 3. 500 kW inverter efficiency comparison.

Figure 4 shows the configuration of a PV system with a unipolar inverter and array in the U.S. Figure 5 shows a PV system with a bipolar inverter and array configuration. It offers lower power loss and component cost due to lower DC and AC current.

Fig. 4. Unipolar PV configuration in U.S.

Fig. 5. Bipolar PV configuration in U.S.

IV. EXISTING PV PROJECTS THAT LOWER BOS COSTS

A. Outdoor PV inverter installation without extra cooling and enclosure costs

Figure 6 shows a real outdoor PV inverter with IP45 protection installed in a hot desert region. Since an enclosure is not required and no energy is lost in keeping the unit cool, BoS savings and higher efficiency add to this system's low LCOE. Similarly, the outdoor inverter installation in Figure 7 shows that an enclosure and heating system are not

required in a cold-weather climate. The above applications save not only BoS costs but reduce the LCOE with low installation costs and high system energy output.

Fig. 6. Hot desert application.

Fig. 7. Cold snow application.

Fig. 8. BoS cost reduction items.

Fig. 8 shows a sample of BoS cost reductions for a utility PV project using a high-quality, transformerless inverter. A PVSYST simulation result for four differently manufactured PV inverters is shown in Figure 9, and it is clear that the high-efficiency, transformerless inverter can generate more AC energy due to higher performance rate. The annual energy for a 10 MW PV site in Dunhuang, China can be calculated based on the SAM model as shown in Figure 10. The lowest LCOE is 20.49 cent/kWh with a better inverter, and it is smaller than other configurations (20.75 to 21.14 cent/kWh) even though the unit price of other inverters is 50% lower. The results would hardly differ, even if these inverters were free.

Fig. 9. Performance rate list.

Fig. 10. Annual output energy comparison for 10MW project.

Fig. 11. LCOE comparison for 10 MW project.

V. CONCLUSION

The main finding of this work is that BoS cost savings can be achieved with a high-performance inverter that also reduces the LCOE (20.49 cent/kWh). Based on the SAM model for a 10 MW PV site in Dunhuang, China, a true, high-efficiency, transformerless inverter can make a sizable difference. Integrators and end-users should consider this model when selecting a suitable inverter for their PV project

and consider the financial result. Note that this study has examined only the effects of the inverter on BoS cost savings and LCOE reduction with limited finance parameters. There is room for further investigation and more detailed study of PV system designs and finance models.

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