Optimal Solar PV Sizing for Inverters Based on Specific Local Climate

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***Abstract*—Generally, the output power of the Photovoltaic (PV) panels is less than the nominal rating of the panel. On the other hand, the inverters of the PV systems are normally sized smaller than the nominal rating of the photovoltaic system. A typical PV to inverter power rating ratio is 1.2, which can be influenced by the weather condition. The main drawback is that during peak irradiance and optimal temperature situation, the peak power is generated at the PV, but the inverter is not sized for absorbing the whole power. This article develops a systematic method to calculate the optimal ratio between PV panel and inverter to absorb the maximum possible power with an optimal cost. This method uses the annual irradiance and temperature of the geographical region and extracts the power curves for a photovoltaic system in specific regions. Based on the distribution of the various weather conditions, the total possible power generation of the system is calculated. Then the possible extracted and lost power for different sizes of inverters are calculated to develop an efficiency function for the extracted power of the typical power system. This function is optimized considering the price of inverters and system. Both of conventional 1000 V PV system as well as recently developed 1500 V system for 480 VAC grid connection are studied and the effect of transformer in both case is investigated. The paper shows how 1500 V system is superior to its 1000 V counterpart.**

***Index Terms*—Grid connected solar generation, optimal power rating, PV panel.**

I. Introduction

The demand for electricity has increased in the last decades as the result of industry and population growth. These parameters have motivated vast research efforts for clean alternative resources for power. Renewable energy resources (RER) are the clean and sustainable alternatives. RERs are environment friendly and their application diversifies the energy resources to improve the energy security [1]. This paper is focused on solar power generation as one of the oldest and most developed types of renewable energy resources. The output voltage of the PV systems is DC, and it includes fluctuation as a result of weather variation. This DC output needs to be properly converted using an inverter before connecting to the conventional AC power system.

The nominal power of the PV panel is calculated based on the maximum irradiance and the base temperature which is $25°C$. However, the output power of the PV depends on the weather condition and most of the times, the output power is less than the rated value [2]. Therefore, sizing the inverter the same as the nominal power of the panel is financially inefficient [3].

There are several researches that have focused on optimal sizing of the inverter, and solar panel to avoid energy loss and achieve more efficiency at the minimum cost. One of the popular methods is Intelligent optimization techniques like a trained neural network to find the optimal PV size. Artificial immune system [4], multi objective bee optimization [5], and genetic algorithm [6], [7] are among them. Although these methods are powerful, a proper tuning is required for any city to get reliable results.

Another popular method to find the optimal PV size, is iterative methods. [2], [8] utilize this method to find the optimal PV. Convergence problem needs to put into consideration when an iterative method is being used due to in loop calculations. Although most of the PV sizing applications are grid connected, some researches suggesting ways to find the optimal value for stand-alone systems [1], [9].

An alternative method which is used in [10], [11] is based on developing an algebraic equation for PV power and solve it for optimal sizing of PV panels. The equation is being solved for a specific inverter based on the extractable energy. For example, article [12] discusses three analytical methods for optimal sizing of the PV inverter. One of the challenges is that the power equation of the PV is complicated to express as an regular algebraic function and hence an approximation of the power function is required. These approximations are usually quadratic functions [10], [11].

There are other papers that consider different criteria to find the PV size as well. [13] investigates the best PV to inverter power ratio that leads to better thermal condition for the inverter and hence a better lifetime expectancy of the overall system. The effect of unique weather condition like high-latitude maritime climates are also investigated in [14].

This study develops a direct and accurate method to optimize the solar panel to the inverter power ratio for a grid connected PV system for different geographical regions. The annual irradiance and temperature for four states with different weather conditions are used. The PV system is simulated in SAM [5] and MATLAB environment.

Articles [11], [15] have used simulation models to find the optimal size of grid connected PV system to increase the yearly energy production. [11] uses an approximation mathematical model of PV power and [15] uses SAM to get the PV data. This paper combines SAM data and PV equation to find the optimal PV size in a grid connected system.

II. Solar PV Equations

General equations (1)-(7) are the basic equations describing the voltage and current characteristics of solar PV panels. Parameters $I_(L, ref), {}_(I, sc), T_cref, I_(o, ref), k, a_ref, R_s, R_(sh, ref)$ are constants that are provided for different solar panels.

$$I = f(V) = I_L - I_o(e^{\frac{V+IR_s}{a}}) - 1) - \frac{V + IR_s}{R_{sh}} \tag{1}$$

$$I_L = n_{sh}(\frac{G}{1000} I_{L,ref} + \mu_{I,sc}(T_c - T_{cref})) \tag{2}$$

$$I_o = n_{sh} I_{o,ref}(\frac{T_c}{T_{cref}})^3 e^{(\frac{1}{k}(\frac{1.12}{T_{cref}} - \frac{E_{bg}}{T_c}))} \tag{3}$$

$$E_{bg} = 1.12(1 - 0.0002677(T_c - T_{cref})) \tag{4}$$

$$a = n_s a_{ref} \frac{T_c}{T_{cref}} \tag{5}$$

$$R_s = R_{s\ cell} \frac{n_s}{n_{sh}} \tag{6}$$

$$R_{sh} = R_{sh\ cell} \frac{1000}{G} \frac{n_s}{n_{sh}} \tag{7}$$

where V and I are PV array voltage and current, I_L is the light current, I_o is the diode reverse saturation current, $R_{s\ cell}$ and $R_{sh\ cell}$ are cell series and shunt resistors respectively, G is the effective irradiance in the scale of 0-1000, E_{bg} is cell material band-gap energy in eV, a is Sandia temperature parameter, T_c is cell temperature and T_{cref} is $25°C$, k is Boltzmann constant in eV/K, μ is temperature coefficient. These parameters are extracted from SAM.

The design process of a solar panel system for the case study of this paper starts with selecting a PV panel. Then based on the characteristics of that panel and desired voltage and power of the PV system, the number of series, n_s, and parallel, n_{sh}, panels are calculated in (8)-(10).

$$n_s = \frac{V_{panel}}{V_{oc\ cell}} \tag{8}$$

$$I_{panel} = \frac{P_{panel}}{V_{panel}} = \frac{P_{panel}}{V_{mppt\ cell} n_s} \tag{9}$$

$$n_{sh} = \frac{I_{panel}}{I_{cell}} \tag{10}$$

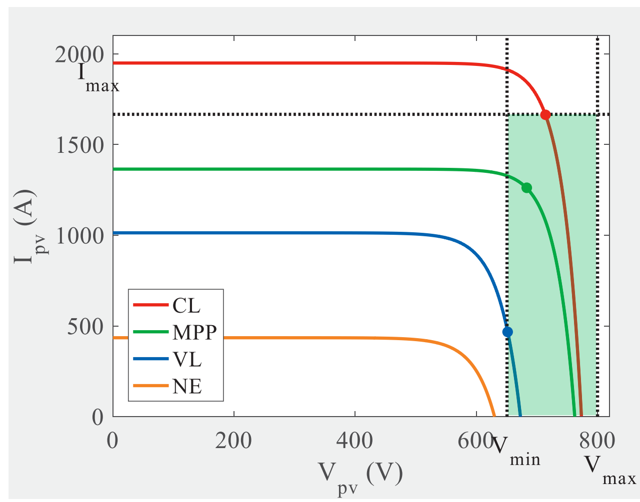
where $V_(occell)$ is the open-circuit voltage of the cell.

Solar Advisor Model (SAM) is a performance and financial model designed to facilitate decision making for renewable energy systems. Weather information for various locations have been adopted from SAM, which uses the above equations.

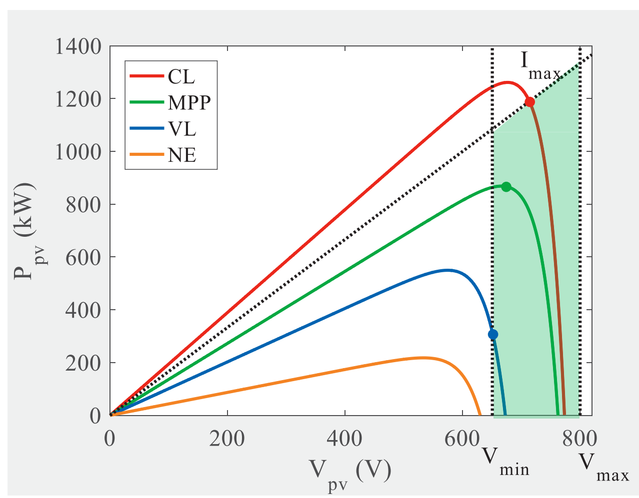
III. Modes of Operation Based on Voltage and Current Limitations

Solar PV sizing is described for four states in the US with significantly different weather conditions. These states are chosen to be diverse in irradiance and temperature. Wisconsin is chosen as a cold state, Arizona is considered as a warm region with high irradiance, Washington state is a region with mostly cloudy weather, and Tennessee is selected as a state with milder weather condition.

The PV side voltage of a grid connected system should be higher than twice of the phase peak AC voltage. Usually, a boost transformer is used to match the lower inverter AC voltage to the higher utility voltage, making the power transfer feasible at lower PV voltage. Hence, the minimum voltage line in Figure 1 is determined by the transformer turn ratio. The voltage and current rating limits of the switching power modules in the inverter determine the maximum operating voltage current which are shown in Figure 1 with dotted lines. There are four possible modes of operation for the PV panels in each of these four regions based on the weather conditions. The green area is the feasible operation range of the PV system.



(a)



(b)

Fig. 1: PV curves, voltage, and current limitations: (a) current vs voltage ; and (b) power vs voltage.

- Current Limit (CL): If the irradiance is high enough that the maximum power point MPP current is higher than the inverter current limit, the current has to be limited to the maximum current which leads to higher voltage and lower power.

- MPP:The MPP current is lower than the current limit, and the MPP voltage is higher than the minimum voltage. MPP power can be extracted from the PV.
- Voltage Limit (VL): The MPP voltage is lower than the minimum voltage, and the open circuit voltage is higher than the minimum voltage. The operating point voltage should be the minimum voltage which results in the power lower than the maximum.
- None Extractable (NE): The open circuit voltage is lower than the minimum voltage, and hence the PV curve is outside of the operate-able region.

While the acceptable voltage range can be extended by choosing a higher ratio for the transformer, the current limit depends on the rating of the inverters and increasing the maximum current limit needs more parallel modules. The flowchart in Figure 2 shows the applied logic for categorizing the modes of operation for different weather conditions. The annual hourly based irradiance and temperature of the four states are used to calculates maximum power point voltage, current, and the open circuit voltage. For the CL condition, the current of the PV is known, and the voltage needs to be calculated based on the current. Equation (11) shows the inverse PV equation. For the MPP condition, the PV power is simply MPP power. In the VL condition, the voltage of the PV is equal to the minimum voltage, and the current has to be calculated from equation (1). For the NE condition, the power is simply zero.

$$V = f^{-1} = a \ln \frac{I_o - \left(1 + \frac{R_s}{R_{sh}}\right) I + I_L - \frac{V}{R_{sh}}}{I_o} - IR_s \quad (11)$$

Table I summarizes the average irradiance, temperature, and the ratio between average extractable power and the ideal case power when irradiance is always at maximum for each of these states.

TABLE I: Differences between weather and PV generations for four states

	G_{ave}	$T_{cave}{}^{\circ C}$	P_{ave}/P_{max}
Wisconsin(WI)	160	8	14.8
Arizona(AZ)	241	22.5	22.7
Washington(WA)	139	11	13
Tennessee(TN)	193	17	18

Figure 3 shows the average PV curves for each state. The differences between the weather of these states can be easily noticed on the curves. The average PV power curves do not represent the average annual power but the curves are for average temperature conditions and are easy approximations to get some insight on total energy generation. This approximation is used for describing the logic behind the developed method. As the figures show, WI has the highest voltage corresponding to the minimum temperature and AZ has the highest current/power corresponding to the maximum irradiance. The energy yield is the highest in AZ followed by Tennessee.

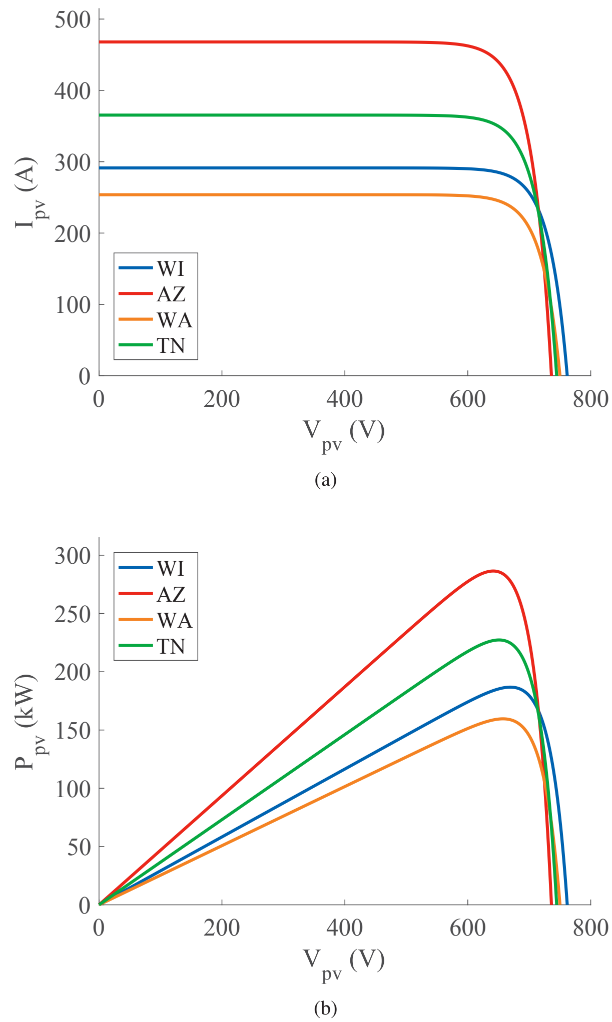


Fig. 3: : Average PV curves for several US States: (a) current vs voltage ; and (b) power vs voltage.

IV. DATA ANALYSIS AND INTERPRETATION

The annual report of Wisconsin for a typical transformer and inverter is shown in Figure 4. The cumulative time, represents the percentage of the time of the year, the PV system operates at each of the mentioned modes. Cumulative power on the other hand, shows the percentage of the power obtained from each of these modes during a year. For any hour, the condition is being checked to determine the mode. When the mode is detected, the hourly power is being added to the cumulative power of that mode and one hour is being added to the corresponding cumulative time. The cumulative time function describes how often any of the modes happens during a year. As it is shown in Figure 4(a), although the time of the CL in this instance is only 5%, the corresponding power is 25%

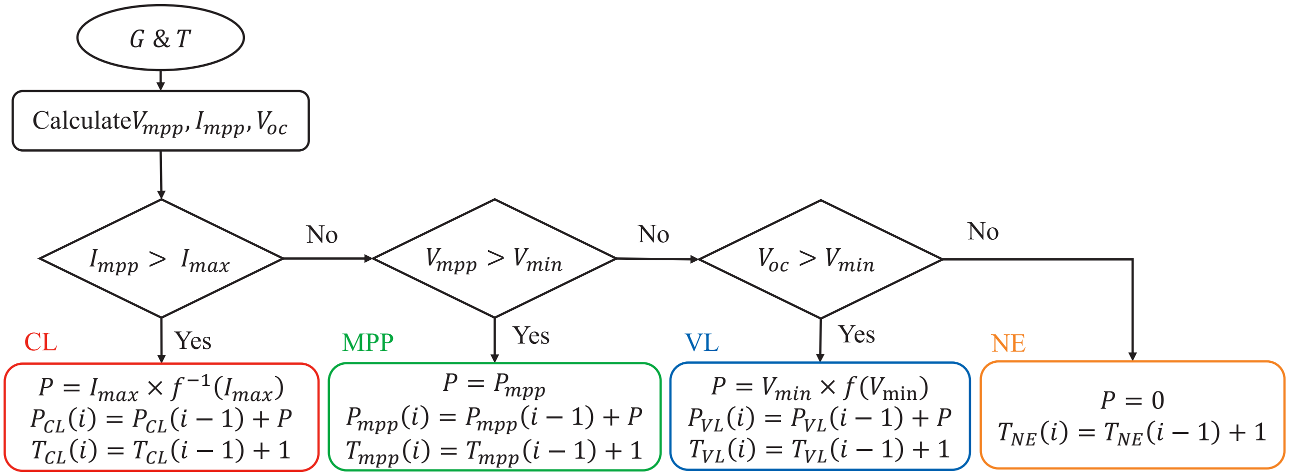


Fig. 2: Flowchart of the power and time categorization

because the irradiance is at maximum in this condition. The potential power if Figure 4(c), shows 96% of the available power of the PV side is transferred to the utility. The 4% non-transferable power is half due to the current limit and half to the voltage limit. The described algorithm in flowchart of Figure 2 has been applied to the annual data of the states with a 1:2 boost transformer which extends the acceptable voltage range long enough to almost eliminates the power loss due to the voltage limit. The number of the parallel inverter is increased in each run to raise the limit for the maximum current. The total cost in Figure 5 shows that around 70 of the system cost is the cost of PV. The system cost linearly increases by increasing the number of inverters. The transferable power if Figure 5 is the percentage of the PV power which can be transferred to the utility. Having more inverters helps extracting more power, but it saturates at a point that the inverter current limit exceeds the maximum PV current. Cost over power in Figure 5 is the total cost divided by the transferable power and the minimum value of this function indicates the optimal cost per power.

Although it is easier to consider a certain PV panel and find the optimal size inverter, in a real application, solar plant with a nominal power has inverters with the same power and an oversized PV panel. Hence, the results shown in Figure 5 are reconfigured to generate Figure 6 for four states. This figure shows the percentage ratio of the total cost per transferable power versus the PV to the inverter power ratio. The minimums value of each curve is the optimal PV to inverter ratio for that state. These minimum values are shown in Table II. Also, Table II shows the ratio of the transferable power to the total available power of the PV panel which is calculated based on the flowchart of Figure 2. A 380:480 transformer is considered between the inverter and 480 utility to calculate the actual transferred power percentage.

V. Case of 1500V

1200 V MOSFET have dominated the market as the industry standard for a long time and 1000 V PV system are being built based on this technology. Recently, 1700 V have been commercialized which opens the possibility to shift the PV technology to 1500 V systems. However, this voltage change would affect the design parameters of the power conversion stages of the system. This section compares these two PV systems at the same power and discusses the ratio of the PV to the inverter power for the 1500 V system. Figure 7 shows the counter part of Figure 6 for 1500 V system.

TABLE II: Optimal PV to inverter power ratio for 1000 V system.

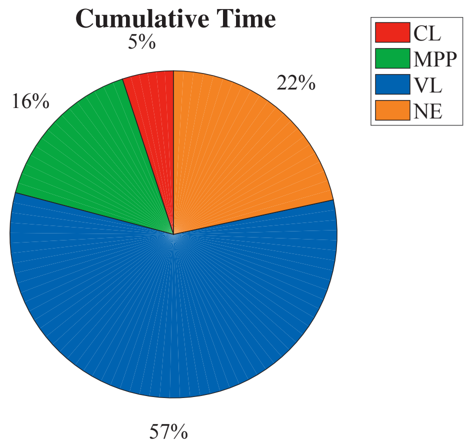
	PV to inverter power ratio	Actual transferred power percentage
Wisconsin(WI)	1.4065	96.84
Arizona(AZ)	1.1688	88.84
Washington(WA)	1.4041	96.59
Tennessee(TN)	1.3186	94.91

Table III shows the actual transferred power and PV to inverter power ratio for two similar PV systems with different dc voltage of 1000 V and 1500 V for the four states. The same 380:480 transformer is considered again to have a fair comparison. These calculated optimal ratios are different and the PV system with higher voltage has lower ratio. For instance, in Wisconsin, for a 1 MW inverter, the optimal PV power is 1.33 instead of 1.4 MW which means fewer number of cells are required. The PV array in 1500 V system will be cheaper and PV array is the most expensive component of the Solar system compared to the inverter and transformer.

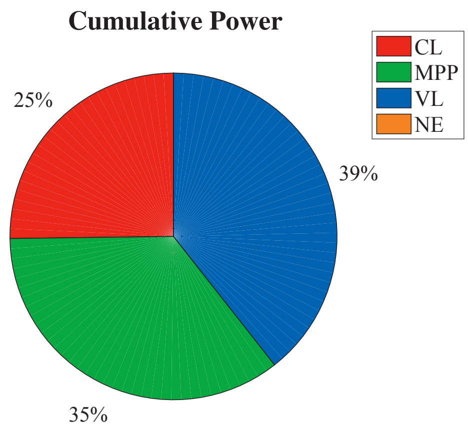
Seasonal weather change, varies the optimal value but since the installation of PV panel cannot be changed for every season, this paper look at the annual data and suggest an optimal ratio for the whole year.

VI. Effect of the Transformer

The comparison between the percentage of transferred power in two systems with dc voltage of 1000 and 1500V with various transformers have been discussed in this section. Three



(a)



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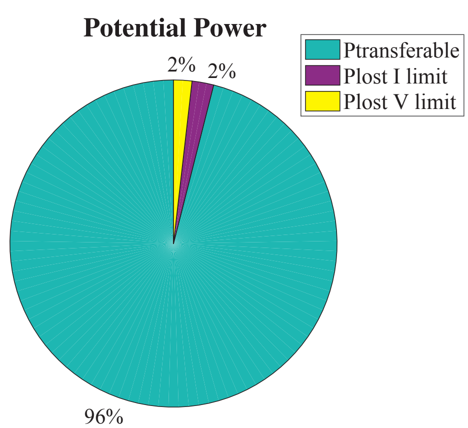

(c)

Fig. 4: The cumulative time and power share of each condition for Wisconsin: (a) cumulative time; (b) cumulative power; and (c) potential power

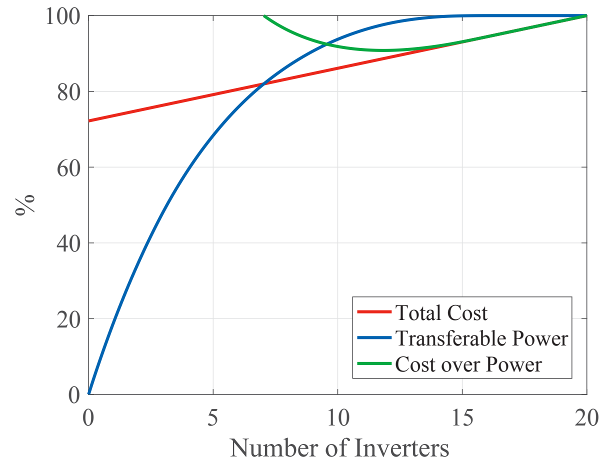

Fig. 5: Cost, power, and ratio of them for Wisconsin 1000 V system.

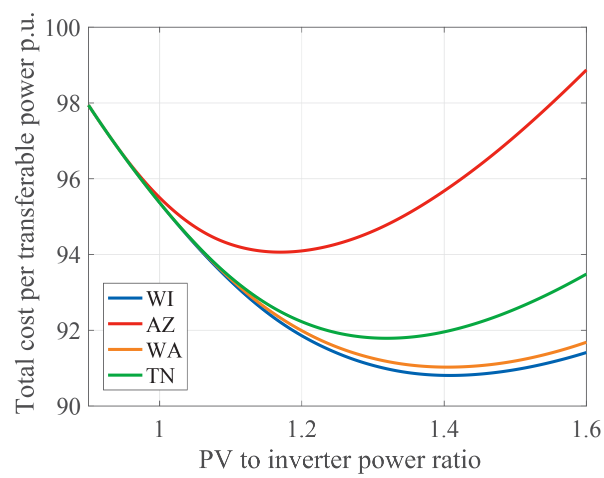

Fig. 6: PV to inverter power ratio for 1000 V system.

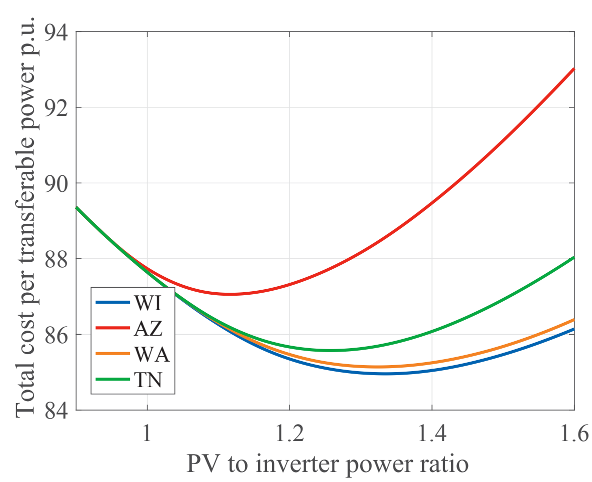

Fig. 7: PV to inverter power ratio for 1500 V system.

TABLE III: Optimal PV to inverter power ratio for 1500 V system.

	PV to inverter power ratio	Actual transferred power percentage
Wisconsin(WI)	1.3345	96.73
Arizona(AZ)	1.1167	87.33
Washington(WA)	1.3243	96.47
Tennessee(TN)	1.2568e	94.80

typical transformers with the ratios of 240:480, 380:480, and 480:480 have been considered to show the changes in amount of passed power between these two systems. Transformer with low voltage on the PV side reduces the voltage limit power reduction to the transfer power which is named **VL** in the chart of Figure 2.

The actual transfered power to the utility after using the optimal PV to inverter power ratio for 1000 and 1500 V cases are shown in Table IV. The utility receives part of the available power on the PV side due to either voltage or current limit. As expected a boost transformer helps 1000 V system to transfer most of the PV power. Having an 1:1 isolation transformer however, limits the power transfer significantly to less than half of the PV power.

A boost transformer in the case of 1500 V however does not help much as the DC link is much higher and even at lower radiance the AC side voltage is enough to be connected directly to 480 V.

TABLE IV: Transferred power percentage with various transformer and two cases of 1000 and 1500V.

		Transformer ratio		
		240:480	380:480	480:480
1000V	WI	96.6960	96.8443	47.1684
	AZ	89.3170	88.8407	48.5545
	WA	96.4696	96.5924	34.3231
	TN	94.8004	94.9140	43.8541
1500V	WI	96.7302	96.7302	96.7305
	AZ	87.3338	87.3338	87.3184
	WA	96.4716	96.4716	96.4718
	TN	94.8028	94.8028	94.8004

VII. Conclusion

This research develops a step-by-step method to find the optimal cost effective ratio between the PV panel array size and inverter for different geographical regions. It considers the annual temperature and irradiance of the location and voltage and current limitations of grid-connected PV inverter system. Four US states with drastically different whether conditions are selected to demonstrate the method and the optimal PV to inverter ratios are calculated for them. The cases study is focused on the conventional 1000 V as well as new 1500 V PV panels connected to 480 VAC utility through a boost transformer or without the transformer. The results shows that the boost transformer is absolutely necessary for 1000 V system but not for 1500 V system. Furthermore, the optimal installed power of PV array for 1500 V system is less than its 1000 V counterpart which leads to a more economic solar generation. Having annual irradiance and temperature of any new region, the developed method can be applied and the optimal PV to inverter power ratio being calculated.

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