Distribute Inverter Control Integration in PyPSA

This manual contains a brief explanation of Inverter control strategies namely; fix power factor, power factor as function of active power, reactive power as function of voltage, active power curtailment as function of voltage integration in PyPSA nonlinear power flow or $n.pf()$.

- Inverter control strategies are integrated as component attributes of controllable one port components which are Generator, Load, Store and StorageUnit and their application can be activated via calling $n.pf(inverter\_control = True)$.

- All controllers are coded and stored in pypsa.control.py file, this file is imported and called in pypsa.pf.py while running nonlinear power flow.

1. Distributed Inverter Control

World's trend toward Renewable Energy (RE) due to global warming and low cost of renewables led countries around the world to switch from fossil fuel to RE resources. This change has significant effect in electrical distribution networks due to integration of RE Distributed Energy Resources (DER) such as wind and solar in generation sector and Electric vehicles (EVs) charging stations in the load sector respectively, which will likely affect grid voltage profiles and cause voltage violations in the network [1].

This challenges Distribution System Operators (DSOs) to new grid issues such as voltage violations, thermal overloading of components, e.t.c. These problems limit Integration of further EVs and or DERs in the grid [2]. Among these problems, [3] voltage violation is known to be the most critical one, and DSOs goal is to minimize voltage violation in order to have more room for further integrations, while maintaining the power quality and reliability of the grid stable. Distributed inverter control is one of the modern and efficient techniques to avoid voltage violations by limiting active power injections or reactive power support by inverters. This control technique provides a potential solution to mitigate the mentioned issues and defer investment costs on upgrading the network infrastructures. Therefore, integration of inverter control strategies in PyPSA would be on one hand an interesting feature and on the other hand a useful tool for PyPSA users in this field.

Inverters are semi-conductor devices and are used for conversion of Direct Current DC to Alternate Current AC, traditionally under unity power factor. But inverters can operate under any power factor by changing the phase angle between their voltage and current outputs using the power electronic devices [4]. This characteristic enables DER inverters and EV chargers to support the grid in terms of reactive power compensation under the chosen control type to bring the voltage back to the predetermined allowed range [5]. Inverter reactive power capacity can be flexible and provide both capacitive and inductive reactive power support based on grid need and type of control strategy [6].

Equation 1 [7] below is used for reactive power calculation in each controller, where “p_set” is the amount of generated power and “power factor” is the ratio between the active and apparent power of the connected inverter. According to this equation, reactive power compensation is only available when there is generation, as depicted in figure 1a.

$$q\_out = \mathrm{p\_set} \times \tan(cos^{-1}(\mathrm{power\_factor})) \qquad (1)$$

1.1. Fix power factor Control (fixed_cosphi)

According to reference [7, 8] in this strategy, the power factor of the inverter is fixed to a value usually based on agreement between power producer and Distribution System Operator under regulatory framework, therefore a fixed amount of reactive power will compensated for each generation amount (p_set) per snapshot, and q is the controller reactive power output calculated from equation 1. Figure 1a and 1b depicts the behavior of reactive power compensation for this strategy.

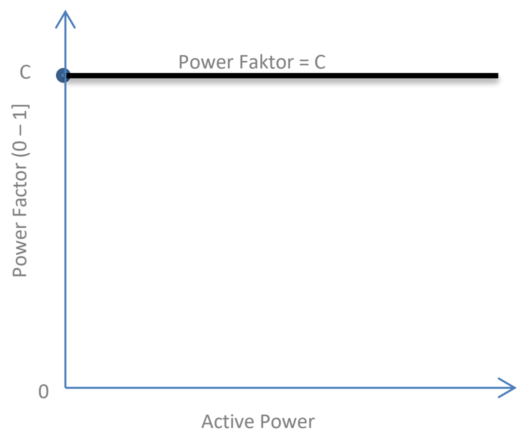


Figure 1a: Schematic of fix power factor control

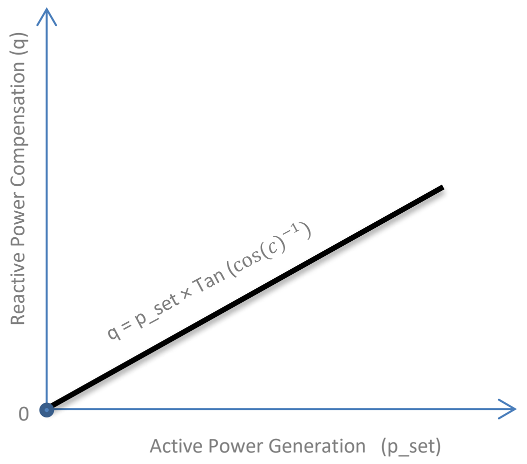


Figure 1b: Reactive power output as active power generation increases

New introduced attributes In PyPSA:

- **S_nom:** Inverter apparent power
- **Power_factor**: The ratio of active power “p_set” to the apparent power “s_nom” of the inverter.

How controller works: The newly introduced attribute “power factor” together with “p_set” is used to calculate the amount of reactive power of the controller as controller output (q_out) using equation 1, q_out as the controller output is then set to the network. From figure 1b, it is clear that reactive power increases as active power generation increases; therefore, “s_nom” is used to limit the amount of reactive power compensation based on inverter capacity (s_nom), for more info read controller reactive power compensation limit.

1.2. Power Factor as Function of Active Power Control (cosphi_p)

According to reference [3, 7, 8], This method is different from the fixed power factor “cosphi” method, in terms that it considers the variable of generated active power and determines the power factor accordingly. This control method avoids reactive power overcompensation from the inverters in conditions when active power generation is low, since subsequent effect of voltage rise will also be below. Therefore, this controller divides power factor in to three zones. In zone 1 power factor is unity due to low power generation, in zone 2 power factor starts to decrease as power generation increases and finally in zone 3 controller works with minimum power factor “power_factor_min”.

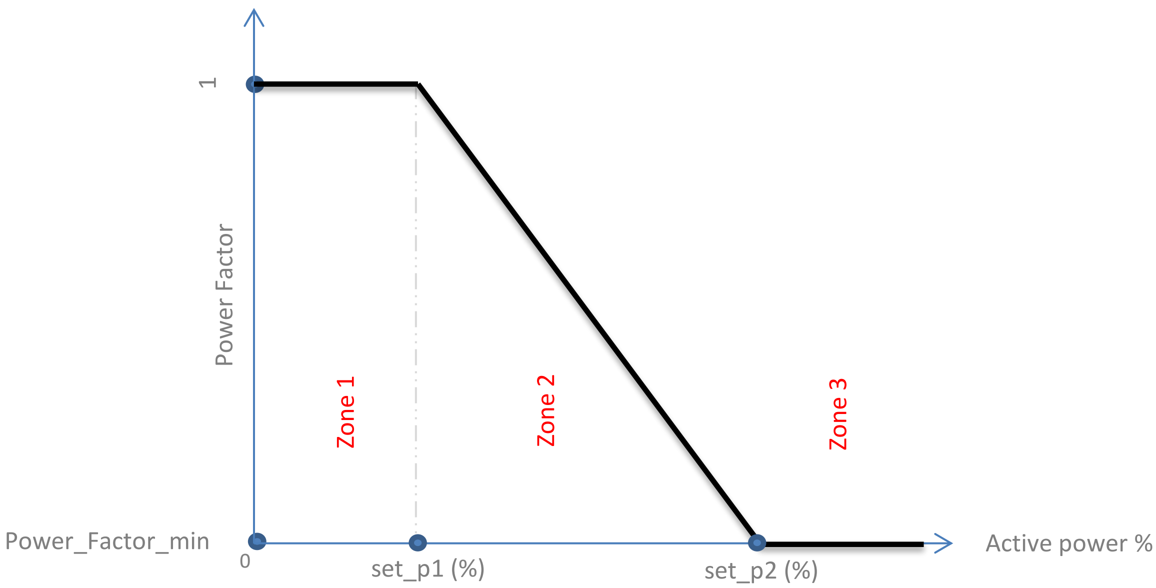


Figure 2: Power factor as a function of active power droop characteristic

The power factor calculation formula for each zone are shown in table 1 along with their conditions.

	Conditions	Power factor calculation	
Power Factor	$\frac{\mathrm{p\_set}}{\mathrm{p\_ref}} \times 100 < set\_p1$	1	(Zone 1)
	$\mathrm{set\_p1} \leq \frac{\mathrm{p\_set}}{\mathrm{p\_ref}} \times 100 \leq set\_p2$	$1-\left(\frac{1-power\_factor\_min}{set\_p2-set\_p1} \times \left(\frac{p\_set}{p\_ref} - set\_p1\right)\right)$	(Zone 2)
	$\frac{\mathrm{p\_set}}{\mathrm{p\_ref}} \times 100 > set\_p2$	$\mathrm{power\_factor\_min}$	(Zone 3)

Table 1: Formulas for power factor as a function of active power control strategy droop curve

New introduced attributes In PyPSA:

- Set_p1: a set point in percentage (see figure 2)
- Set_p2: a set point in percentage (see figure 2)

- S_nom: inverter apparent power, it is used to make sure that sum of active and reactive power $\sqrt{p\_set^2 + q^2}$ is not exceeding inverter capacity "s_nom".
- power_factor_min: minimum power factor that controller will work if p_set / p_ref*100 is greater than set_p2 (see figure 2).
- P_ref: a reference point for controller where controller decides the power factor choice based on p_ref and p_set (see figure 2).

How controller works: P_set attribute of the controlled component is the amount generation or consumption, using "p_set" controller calculates $\frac{\text{p\_set}}{\text{p\_ref}} \times 100$ value and chooses a power factor calculation formula from table 1, once the power factor is calculated, equation 1 is used to find the amount of reactive power compensation (q_out) as the controller output is then set to the network.

1.3. Reactive power as function of voltage Control (q_v):

According to refences [3, 7] this inverter control strategy utilizes its available amount reactive power very efficiently than the other two controllers when it comes to reactive power compensation, such that it provides reactive power support based on voltage information of the bus where this inverter is connected, this way it avoids unnecessary reactive power compensations. For this purpose the droop characteristic for reactive power calculation for this controller is divided in to 5 zones as shown in figure 3 where v1, v2, v3, and v4 are voltage per unit set points for building conditions and choices for each zone.

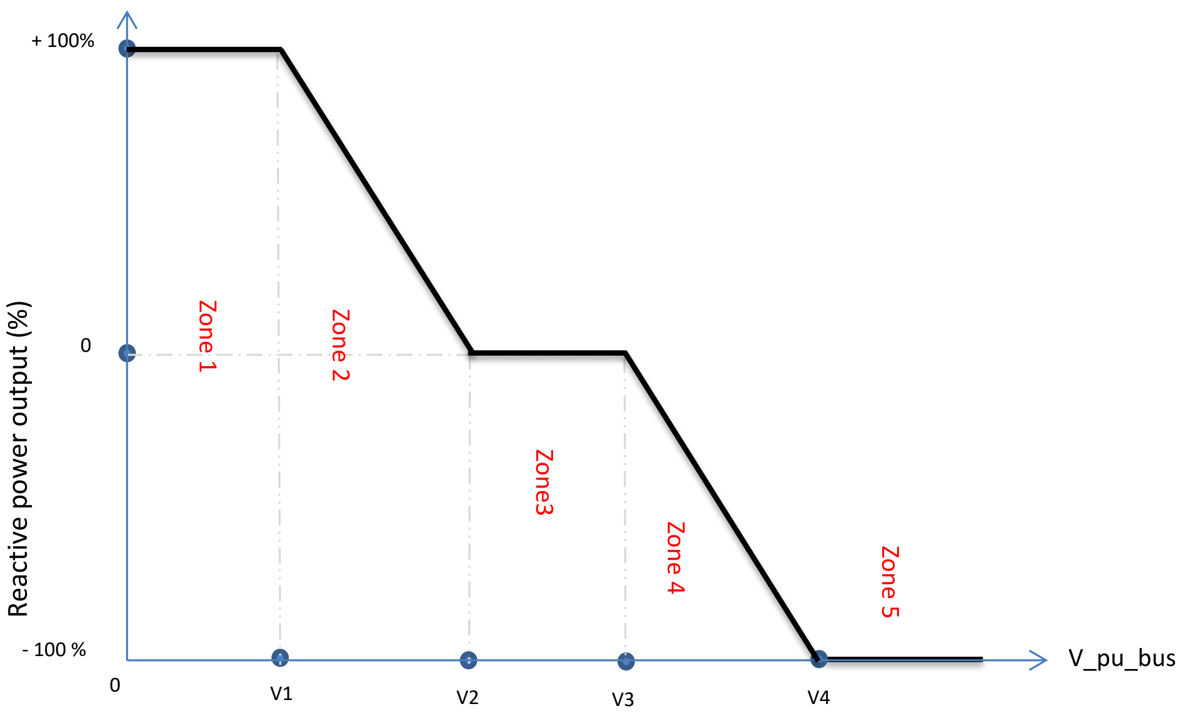


Figure 3: Power factor as a function of active power droop characteristic

The conditions, and choices for each zone are shown in table 2 below:

Reactive power output in percentage	Conditions (per unit)	Reactive power (%)	Zones
	v_pu _bus < v1	100	Zone 1
	v1 =< v_pu_bus = < v2	$100 - (\frac{100}{v2-v1})(\text{v\_pu\_bus} - v1)$	Zone 2
	v2 < v_pu_bus <= v3	0	Zone 3
	v3 < v_pu_bus < = v4	$-(\frac{100}{v4-v3})(\text{v\_pu\_bus} - v3)$	Zone 4
	v_pu_bus > v4	-100	Zone 5

Table 2: Droop characteristic formulas for reactive power as a function of voltage controller

New introduced attributes In PyPSA:

- **v1, v2, v3, v4:** They are voltage magnitude set points in the order of v1 < v2 < v3 < v4 and form the controller droop characteristic curve as shown in figure 4. They form 5 zones where controller compensates differently for each zone. The reactive power calculation for each zone is shown in table 2.
- **Power_factor**: The ratio of active power "p_set" to the apparent power "s_nom" of the inverter.
- **Damper:** A constant multiplied to the output of the controller; it will be needed when controller does not converge due to voltage difference outer loop condition (x_tol_outer) It takes values greater than zero up to 1.
- **S_nom:** Inverter apparent power, which is already introduced by fixed power factor method, this attribute will also be used in "q_v" controller to limit reactive power compensation limit for more info read controller reactive power compensation limit.

How controller works: Controller takes the voltage of the bus where inverter is connected as input and checks the location of the voltage information of the bus on its droop curve (figure 3) and provides a reactive power support in percentage ($curve\_q\_set\_in\_percentage$) from table 2. Then using equation 1 the reactive power output of this controller is calculated as in equation 2 below:

$$q\_out = \text{p\_set} \times \tan(cos^{-1}(\text{power}_{\text{factor}})) \times \text{curve\_q\_set\_in\_percentage (\%)} \times \text{damper} \qquad (2)$$

From equation 2, reactive power increases as active power generation increases, and can go beyond the inverter capacity; therefore, inverter capacity "s_nom" is used to limit the amount of reactive power compensation. For more info read controller reactive power compensation limit.

Controller Reactive Power Compensation Limit

Inverter maximum available reactive power compensation is calculated using equation 3 as follow:

$$q\_available = \sqrt{s\_nom^2 - p\_set^2}) \qquad (3)$$

Where "s_nom" is inverter apparent power capacity and "p_set" is the generated power. For reactive power compensation controllers use equation 1 which is as a function of active power generation, therefore sometimes when generation or "p_set" is maximum, according to equation 3 q_available reduces, in this case inverter fails to fulfil reactive power need because inverter capacity "s_nom" as in equation 4 does not allow it.

$$S\_nom = \sqrt{p\_set^2 + q\_available^2} \tag{4}$$

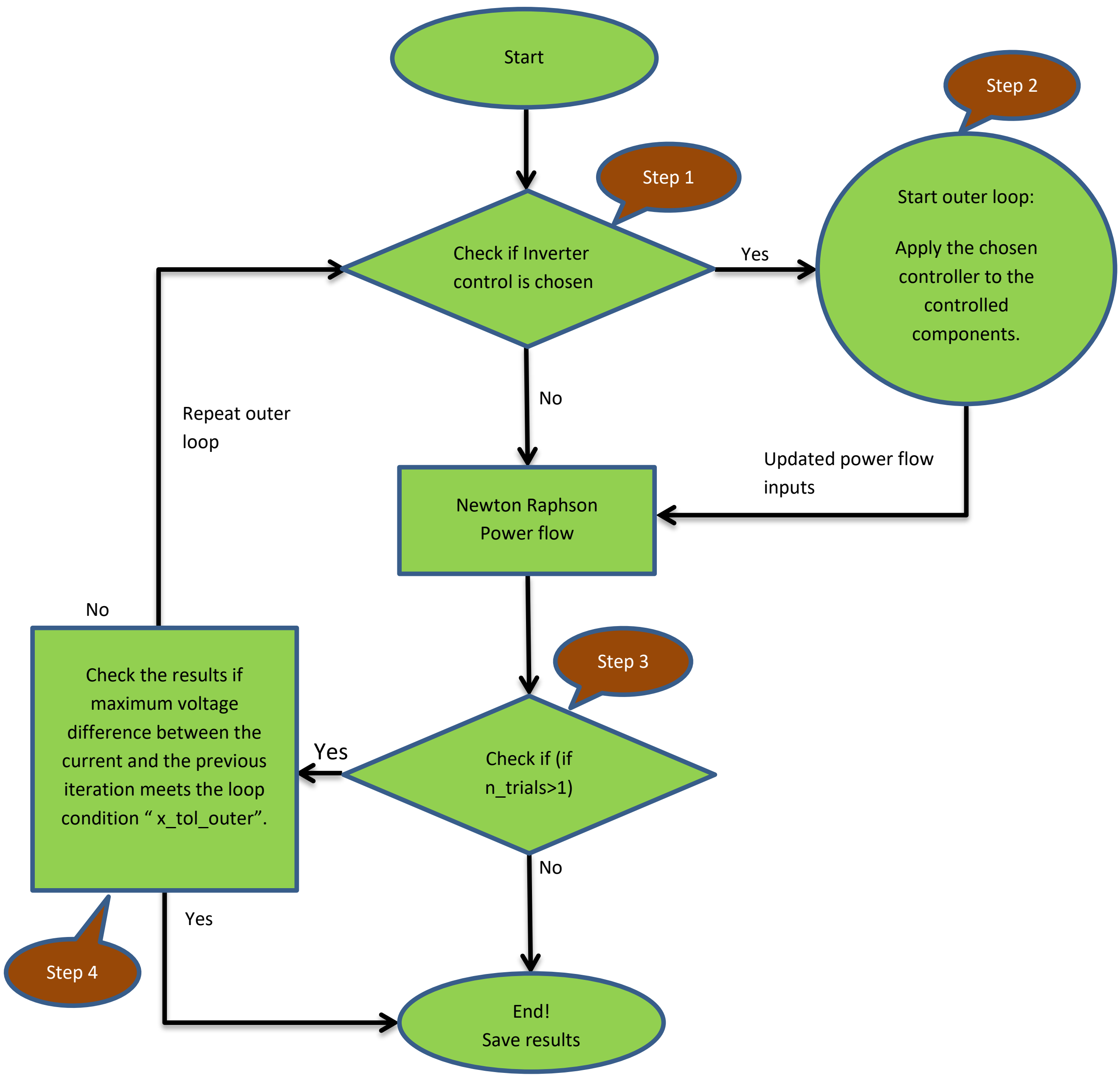
In this case as solution controller reduces p_set to fulfil reactive power need and recalculates active power $p_{set} = \sqrt{s\_nom^2 - q^2}$ and save both p_set and q_out to n.component_t.p or q data frames. But p_set reduction is limited by the provided power factor, the minimum value that p_set can take is determined by equation 5.

$$p\_set = s\_nom \times power\_factor \tag{5}$$

Therefore, when reactive power need increased, p_set can decrease to its minimum values using equation 5 and q_out can take it maximum value using equation 3.

Note: This behavior “reduction of p_set to fulfill reactive power need” is followed from CERBERUS software and is only for fixed power factor and reactive power as a function active power control strategies.

Power flow loop description in four steps



Steps for outer loop:

Step 1: Outer loop which contains application of control strategies activates, when inverter_control is "True" (defaults to False) in n.pf (inverter_control = False). Outer loop applies the chosen control strategy on the chosen components and updates the network.

Step 2: In this step the power flow is run after application of control strategies on the network.

Step 3: n_trial_max is the number of power flow repetition per snapshot. It has a value of 30 trials when the type of control strategy is "q_v" and 1 for other controllers. "q_v" is a voltage dependent controller and to avoid voltage fluctuations due to reactive power compensation there is a voltage tolerance limit between the two consecutive iterations. This tolerance within the power flow loop is called “x_tol_outer”. In each power flow the maximum “v_mag_pu” difference of the current iteration and the previous iteration is compared with the x_tol_outer limit. If voltage difference is less than or equal to x_tol_outer, power flow will converge, otherwise it will keep iterating up to 30 iterations. In the worst-case scenarios when it did not converge, as solution “damper” attribute is introduced which is directly multiplied to the controller output and takes values (0, 1]. Damper values less than 1 will help controller from big swings and finally lead it to converge. Another solution is changing the parameters (v1, v2, v3, v4, power_factor).

Step 4: calculate the voltage difference of previous iteration and the current iteration and compare the result with the x_tol_outer, if the voltage difference is equal or less than x_tol_outer, the condition is met, and the power flow ends here. If not repeat (maximum of 30 iterations) the power flow with the outer loop again until the mentioned condition is met.

References:

1. Bhusal N. The Combined Effect of Photovoltaic and Electric Vehicle Penetration on Conservation Voltage Reduction in Distribution System [Internet]. 2018. Available from: https://digitalscholarship.unlv.edu/thesesdissertations/3218

2. Sherif M. Ismael, Shady H.E. Abdel Aleem, Almoataz Y. Abdelaziz AFZ. State of the art of hosting capacity in modern power systems with distributed generation.pdf. Renew Energy. 2019;130:1002–20.

3. Gómez-González JF, Cañadillas-Ramallo D, González-Díaz B, Méndez-Pérez JA, Rodríguez J, Sánchez J, et al. Reactive power management in photovoltaic installations connected to low-voltage grids to avoid active power curtailment. Renew Energy Power Qual J. 2018;1(16):5–11.

4. Jadeja R, Ved A, Trivedi T, Khanduja G. Control of Power Electronic Converters in AC Microgrid. Power Syst. 2020;27(11):329–55.

5. Hasan, AN, Tshivhase N. Hasan, Tshivhase - 2019 - Voltage regulation system for OLTC in distribution power systems with high penetration level of embedded gener-annotated.pdf.

6. Paudyal S, Ceylan O, Bhattarai BP, Myers KS. Optimal coordinated EV charging with reactive power support in constrained distribution grids. IEEE Power Energy Soc Gen Meet. 2018;2018-Janua:1–5.

7. Demirok E, González PC, Frederiksen KHB, Sera D, Rodriguez P, Teodorescu R. Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids. IEEE J Photovoltaics. 2011;1(2):174–82.

8. Hashemi S, Ostergaard J, Yang G. Effect of reactive power management of PV inverters on need for energy storage. Conf Rec IEEE Photovolt Spec Conf. 2013;2304–8.