An AC PV Module with Reactive Power Capability:

Need and Benefit

Nasser Kutkut
Petra Solar, Inc.

As the solar power market continues to grow, micro inverters and AC PV modules are gaining renewed interest. New advances on power electronics, microprocessors, digital controls, and communications have finally allowed for a new generation of micro inverters and AC PV modules to reach commercial realization.

Micro-inverters are small grid-tie inverters of 150-300W that convert the output of a single PV panel to AC. In this configuration, a single micro-inverter inverter is connected to a single PV panel and is installed close to it. Unlike string inverters, micro inverters offer greater design flexibility, enhanced safety due to the absence of high DC voltage, and increased energy harness due to the single panel MPPT process. In addition, micro inverter based solar power systems are not susceptible to single point failures and are thus more reliable and less costly to maintain.

Although micro inverters offer greater advantages compared to traditional string inverters, AC PV modules offer true modular solar power system, greatly simplify system design and installation, and eliminate safety hazards. The AC PV module is the first to offer a Plug’N’Gen solar power system.

In addition to the above benefits of AC PV modules, Petra Solar’s new SunWave™ AC PV module incorporates new functionalities that greatly enhance the quality and performance of the AC utility grid. This includes an integrated reactive power generation capability, which allows the SunWave™ Solar AC Module to generate up to 100% reactive power (VARs). This unique capability allows the SunWave AC PV module to provide true reactive power compensation to meet the reactive power demand by the distributed loads and improve power factor.

The Need for Reactive Power

Reactive power refers to the circulating power within utility grids that does no useful work. It results from energy storage elements in the utility grid, mainly transformers, transmissions lines, and motors that generate lagging power factor (consume reactive power). It has a strong effect on system voltages and must be maintained in balance in order to prevent voltage problems. Significant capacitance is employed to offset the reactive loads and line voltages must be raised to push power through the lines. The greater the distance from the transmission of power to consumption, the higher the voltage needs to be raised.

Reactive power is primarily required for voltage support, i.e. to maintain the voltage of the electric power system within well defined limits. Inadequate reactive power supply causes the
power system voltage to drop which results an increase in line current flow to maintain a constant power supply. The increase in line currents further increases the reactive power consumption of the lines causing the voltage to drop further. If the current continues to increase, the transmission line may trip or go off-line which may lead to overloading other lines and potentially causing cascading failures. If the voltage drops too low, some generators will automatically disconnect to protect themselves.

Voltage collapse occurs when an increase in load or loss of generation or transmission facilities causes dropping voltage, which causes further reduction in reactive power from capacitors leading to further voltage decline. If the declines continue, additional elements will trip leading to further decline in voltage and loss of load. The result is a progressive and uncontrollable decline in voltage caused by the lack ample reactive power supply by the power system to meet the load reactive power demand.

In summary, reactive power generation is critical to grid performance. Ample supply of reactive power is critical to prevent component damage, such as overheating of generators and motors, to reduce transmission losses, to allow the power system to withstand disturbances, and to prevent voltage collapse.

**AC PV Module with Reactive Power Control**

The SunWave™ Solar AC Module can be modeled as two current sources in parallel as shown in Fig. 1. The amplitude of the first source, \( I_P \), is proportional to the maximum power available from the PV cells, and its frequency and phase are equal to those of the voltage of the mains. The amplitude of the second source, \( I_Q \), depends upon the reactive power commanded by the central command and control center. It has the same frequency as the voltage of the mains, but it is 90° out of phase with it. The behavior of the system is such that the SunWave™ Solar AC Module acts as a shunt active filter supplementing reactive current demand by the distributed loads.

![Figure 1: The SunWave Solar AC Module Equivalent Circuit](image)

The reactive power generation capability is achieved by integrating a four quadrant inverter capable of operating as a lead compensator of reactive power. Although this may cause a slight
drop in inverter efficiency, the ability to dispatch reactive power throughout the distribution network improves the transmission and distribution system efficiency and reliability.

The reactive power capability of the SunWave™ Solar AC module can be dispatched using a reactive power command (Q), which can be relayed to the SunWaveTM Single panel inverter via the optional communication module. Figure 2 shows the operation of the SunWaveTM Solar AC module with varying levels of reactive power commands. Note that although reactive power is dispatched, the inverter continues to operate at full maximum power limited only by the volt-ampere (VA) rating of the inverter. The inverter is also capable of dispatching reactive power with no real power as shown in Figure 2(d). This may be the case when excess solar generation is present so as to limit the voltage rise in the distribution network.

![Figure 2:](a) No Reactive Power - 0 VARs; 100% Real Power - 200 W (b) Reactive Power = 100 VARs; Real Power = 179 W (c) Reactive Power = 200 VARs; Real Power = 150W (d) 100% Reactive Power - 200 VARs; No Real Power - 0 W

© Petra Solar Inc.
Benefits of Distributed Reactive Power Supply

The integrated VAR capability of Petra Solar’s SunWave™ Solar AC module provides localized reactive power generation throughout the distribution network that can greatly improve the power factor of distributed loads and reduce the reactive power flow across the transmission and distribution network. This leads to lower current flows throughout the network which yields many advantages can be realized including:

1. **Reduced Transmission Line Losses**

To help show the benefits of distributed reactive power supply, a simple system is presented, as shown in Figure 3 below. The simple system shown below consists of a generation bus, a load bus, and a line connecting the two buses. Assuming that the load power factor is 0.90, the real power (P) consumed by the load is 1 MW, the resulting reactive power (Q) will be 0.484 MVARs.

![Figure 3: A simple one-line power system](image)

To show the impact of localized reactive power generation, it is assumed that a compensation device at the load side will inject a \( Q_c = 0.156 \text{ MVAR} \) to increase the load power factor 0.95. The resultant real and reactive power supplied by the generator are \( P = 1 \text{ MW} \) and \( Q = 0.329 \text{ MVAR} \).

Injection of reactive power at the load side may raise the voltage and reduce the line current. Since the real power loss is \( I^2R \), the line losses will be lower if the current is reduced assuming that the load-side voltage remains the same. Without compensation, the line loss is given by

\[
P_{loss} = I^2R = \frac{P^2 + Q^2}{V^2} \quad R = \frac{1^2 + 0.484^2}{V^2} \quad R = 1.235 \frac{R}{V^2}
\]

The line loss with reactive power compensation of 0.156 MVARs is given by

\[
P_{loss} = I^2R = \frac{P^2 + Q^2}{V^2} \quad R = \frac{1^2 + 0.329^2}{V^2} \quad R = 1.108 \frac{R}{V^2}
\]

As a result, the reduction in line losses will be

\[
\frac{1.235 - 1.108}{1.235} = 10.3\% \text{ for every 0.156 MVAR compensation}
\]
If the total system loss is 3%, the savings in losses will be:

\[ 1 \text{ MW} \times 3\% \times 10.3\% = 0.00309 \text{ MW} = 3.09 \text{ kW} \]

The savings associated with the reduced line losses can be significant if VAR compensation is maintained during peak hours throughout the year, which translates into a net of 4 months over the course of a year. Assuming an annual average utility cost for 1 MWh energy is $102/MWh during peak hours\(^1\), the total savings will be:

\[ $102/\text{MWh} \times 0.00309 \text{ MW} \times 120 \text{ days} \times 24 \text{ hours} = $907/\text{year} \]

Note that the above savings are generated from 0.156 MVAR of compensation. Therefore, the savings for every MVAR of reactive power compensation will be $5,814/MVAR-year. Note that the actual savings should be slightly higher since the terminal voltage \( V \) should be slightly higher due to the reactive power compensation.

2. **Increased Line Capacity**

The injection of reactive power leads to reduced line current flow and increased transmission line capacity. In the previous example, the injection of reactive power to increase the load power factor to 0.95 will also lead to reduced line current. This is equivalent to having a distribution or transmission line with higher KVA capacity rating.

For the previous one line system, the line current without compensation is given by,

\[ I = \frac{\sqrt{P^2 + Q^2}}{V} = \frac{\sqrt{1^2 + 0.484^2}}{V} = \frac{1.111}{V} \]

The line current with reactive power compensation is given by,

\[ I = \frac{\sqrt{P^2 + Q^2}}{V} = \frac{\sqrt{1^2 + 0.329^2}}{V} = \frac{1.053}{V} \]

As a result, the reduction in line current is given by,

\[ \frac{1.111 - 1.053}{1.111} = 5.2\% \]

The capacity of the transmission line is therefore increased by 5.2% allowing for additional dispatch of inexpensive power to the load side as compared to adding expensive load side generation. As such, an additional 0.052 MW can be transferred over from generation center to load side for every 1 MW load.

The savings associated with the increased line capacity can be calculated by considering the case when the line reaches its max limit during peak hours (4 net months over the course of the year). Assuming an average price difference of $10/MWh between the generation center and the load pocket\(^2\), the total savings over the 4 peak month period will be:

\[
$10/\text{MWh} \times 0.052 \times 120 \text{ Days} \times 24 \text{ hours} = $1,498/\text{year}
\]

These savings are generated from 0.156 MVAR of compensation. Therefore, the savings for every MVAR of reactive power compensation will be $9,602/MVAR-year.

**3. Increased Maximum Transfer Capability**

The maximum transfer capability of the sample system is given as:

\[
P_{\text{max}} = \frac{E^2 (-k + \sqrt{1 + k^2})}{2X} \quad \text{where} \quad E = V \quad \text{and} \quad k = \frac{Q}{P}
\]

Again, assuming reactive power compensation reactive of 0.156MVARs (the power factor from 0.90 to 0.95 or from 1MW +j0.484MVAR to 1MW + j0.329MVAR) and that the voltage remains constant, the max transfer capacity will be improved by 15.5%. Therefore, during the 4 months of peak load, the system can transmit 15.5% more inexpensive MW from the generation center to the load pocket while keeping roughly the same voltage stability margin. Assuming a price difference of $10MWh between the generation center and the load pocket, the dollar savings associated with the increase in transfer capacity is:

\[
$10/\text{MWh} \times 0.155 \times 120 \text{ days} \times 24 \text{ hours} = $4,464/\text{year}
\]

If the compensation is scaled to $/MVAR, it is as significant as $28,615/MVAR-year.

As stated in the previous section, the entity that benefits from such savings is the utility and/or transmission company since they are the network owners.

It should be noted that many other benefits can be realized that may be difficult to quantify such as improved voltage regulation and voltage quality as well as more reliable transmission network with reduced current flows.

**Efficiency Considerations**

In addition to the above discussed improvements, the built-in VAR capability of the integrated SunWave™ inverter results in an increase in overall generation efficiency. In order to show the cost savings associated with the VAR capability, a look at the standards developed by the NERC and its ten Regional Reliability Councils for ensuring the reliability of a transmission grid will help establish some basis for such analysis. These include:

\[^{2}\text{"Transmission Rights and Market Power", Peter Cramton, 2004}

© Petra Solar Inc.
- Balance reactive power supply and demand to maintain scheduled voltages
- Keep the system in a stable condition
- Plan, design, and maintain the system to operate reliably

To accomplish the above goals, institutional arrangements for reactive power compensations have been developed. Generally speaking, ISOs and RTOs do compensate generators (both affiliates of vertically integrated utilities and IPPs) for providing reactive power. The institutional arrangement is compensation using a cost-based schedule set in advance, usually a payment equal to the generation owner’s monthly revenue requirement. In exchange the generators must be under the control of the control area operator and be operated to produce or absorb reactive power. In some cases when there is a reduction in real power output due to a request for reactive power production, the RTO will provide an additional payment to compensate the generator for the lost opportunity of delivering real power into the network. According to a DOE report on the economics of using distributed energy sources for reactive power, payments to independent power producers for generation voltage support in terms of reactive power reserves vary from $1,050 to $10,000 per MVAR per year\(^3\). The average payment to independent generators for reactive power is roughly $4,000 / MVAR / year.

With the SunWave Solar AC module and assuming a 200W rated inverter, the total annual power generation capacity of a single module is calculated below:

\[
\text{kWhrs generated per year} = 675 \text{ Whrs / day} \times 365 = 246 \text{ kHrs / year / panel}
\]

Note that the average daily Whrs generation capacity of a single panel is 675 Whrs, which is computed using the PVWatts derating factor and assuming a 30° angle.

The benefit of the integrated VAR capability can be calculated using the average $50 / kVAR, or $10 for a 200VAR panel. If the life of the inverter is amortized over 10 years, this translates into $1.0 per panel per year of integrated VAR generation capacity. In addition, utilities could save on compensation payments due to the integrated reserve VARs, which would otherwise be allocated to independent generators. The compensation payments cost savings can be calculated using a $4,000 per MVARs per year. For a 200VAR panel, the cost savings would be $0.8 per panel per year. As such, the total savings would add up to:

\[
$1.00 \text{ for integrated VAR capacity} + $0.80 \text{ compensation payment savings} = $1.80 \text{ total cost savings.}
\]

This results in additional revenue of $1.80 per panel per year. Assuming an average solar power generation cost of $0.3/kWhr, the additional revenue can be translated into equivalent solar power generation of:

\[
$1.8 / $0.3 = 6 \text{ kWhrs equivalent additional annual generation}
\]


© Petra Solar Inc.
This represents an effective inverter efficiency gain of:

\[
6 \text{ kWhrs} / 246 \text{ kWhrs per year} = 2.43\%
\]

As such, and assuming a base CEC efficiency of 93%, the effective inverter efficiency will be 95.43% due to the built in VAR generation capability.

**Conclusion**

In summary, the SunWave™ AC PV module VAR generation capability contributes to a greater AC system stability and considerable energy savings.

**References**