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Effect of Non-unity Power Factor Operation in Photovoltaic Inverters Employing Grid Support Functions

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ABSTRACT — The high penetration of utility-interconnected photovoltaic systems is causing heightened concern over the effect that variable renewable generation will have on the electric power system (EPS). These concerns have initiated the need to amend the utility interconnection standard to allow functionalities, so-called *advanced inverter functions*, to minimize the negative impact these variable distributed energy resources may have on EPS voltage and frequency. Unfortunately, advanced functions, in particular volt-VAr, will result in non-unity power factor (PF) operation [3]. The increased phase current results in additional conduction losses and switching losses in the inverter power electronics. These power losses have a direct impact on real power delivered to the grid at the point of common coupling (PCC) and an impact on inverter service life. This report provides analysis, simulation, and experimental evidence to investigate the effect of *advanced inverter functions* on non-unity PF operation.

Index Terms — advanced inverter functions, distributed energy resources (DER), non-unity, power factor.

I. INTRODUCTION

Utility-scale power is characterized by rather precise control of both frequency and voltage. These are accomplished by speed governor control of synchronous generators for the first, and excitation control and tap-changing transformers for the second. As more distributed renewable generation is incorporated into the grid, well-regulated conventional generation will be displaced by stochastic energy sources, which are likely to contribute to voltage disturbances and frequency-regulation difficulties [1]. Negative impacts of high-penetration photovoltaics (PV) may also include reverse power flow, power fluctuations, power factor (PF) changes, unintentional islanding, and fault currents.

It is established that reactive compensating devices may be used to improve voltage stability [2]. Thus, it's been suggested that allowing distributed generation inverters to provide reactive power support can improve voltage regulation.

A. Advanced Inverter Function

Reactive power support can be operated autonomously through a programmed response to voltage at the point of common coupling, or the reactive power can be selected through an explicit PF command. The function that defines the voltage to reactive power relationship is called the *volt-VAr* function and this function along with other commanded and autonomous utility grid support functions are defined in the IEC 61850-90-7 standard [3].

In general, the control is intended to provide negative feedback to the grid in response to voltage variation, but there are several different variations (modes) for implementing the volt-VAr control. An overview of the volt-VAr function is given in Section II, and the effects on power factor and conversion efficiency are discussed in Section III. Conclusions are provided in Section IV.

II. REACTIVE POWER FUNCTIONS

A utility-interconnected PV inverter's normal operational mode is to convert all available energy from the dc source into kWh_{ac} in the most efficient and effective manner. Thus, *maximum power point tracking* (MPPT) is the standard mode of operation. The objective is economically motivated; PV system owners are compensated for kWh delivered to the grid, and the system investment has the best rate of return if it operates as intended. The recent desire for PV systems to produce anything other than real power is driven by system operator acknowledgement that a high level of PV system adoption can lead to electric power system (EPS) instability if the penetration level for a given locality rises to a point where the distributed energy resources (DER) can influence the voltage of the local EPS.

A. Volt-VAr Function (VV11–VV14)

The utility interconnection standard [4] is presently undergoing revisions that will allow DER devices to assist in voltage-regulation functions [5]. The EPS owns voltage-regulation requirements and duties. However, recent changes to the interconnection standard allow the DER to participate in voltage-regulation requirements. Implementing the volt-VAr function enables DER voltage-regulation capabilities that can respond to a change in line voltage that exceeds the predetermined deadband voltage. This function has different means of implementation, and each method has power-generation priorities. The function description defines how a DER inverter provides the EPS with reactive power for voltage support. The system operator can implement the volt-VAr function in four possible modes.

- VV11: Provide a certain percentage of available Vars, based on the system voltage. No effect on watt generation. This function can be autonomously implemented.
- VV12: Provide the maximum Vars possible during certain conditions, as when system voltage is within specified ranges. This command may result in a reduction in real power generation. This function can be autonomously implemented.
- VV13: Fixed settings to provide Vars as a function of equipment under test (EUT) output level. These settings do not vary with system voltage. This is a commanded function and requires communication to DER.
- VV14: Provide maximum active power (unity PF, with no Vars). This is the default setting.

The volt-VAr function is best presented as a curve, which shows the voltages and reactive power values that are programmed as percentages of nominal line voltages and as a percentage of available or maximum reactive power. See Figure 1. The voltage pairs, V2–V3, are considered the deadband around nominal line voltage and are typically 1% or 2% of nominal voltage. The reactive power at the nominal line voltage, Q2–Q3, will typically be set to 0 and the voltage pairs V1–V4 are typically set to 3% or 4% of nominal line voltage. The reactive power pairs Q1–Q4 are either a percentage of available Vars or the maximum available.

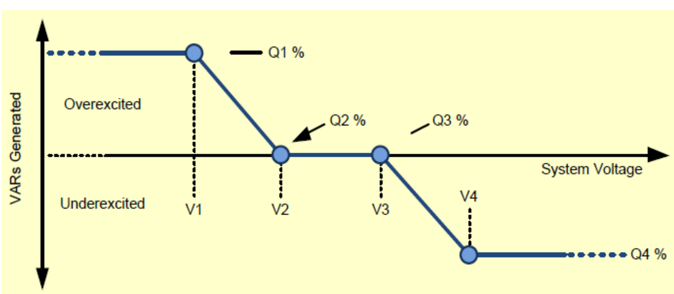

Figure 1: V1–V4 are the adjustable voltage percentages and Q1–Q4 are the adjustable reactive power percentages

Table 1 is used to assess the voltage-regulating function and the capability of adjustability and conformance to set values. The device under test is programmed to these set values and a data-acquisition system captures the data.

Table 1: Volt-VAr parameter settings

EUT Initial Operating State	Volt/Var Initiation	Volt/Var [V,Q] Array			
50% rated power, unity PF	Binary, 1	V1	97	Q1	50
		V2	99	Q2	0
		V3	101	Q3	0
		V4	103	Q4	−50
90% rated power, unity PF	Binary, 1	V1	97	Q1	50
		V2	99	Q2	0
		V3	101	Q3	0
		V4	103	Q4	−50

B. INV3 Commanded Power Factor Function

Another method used to control the displacement angle of the current is the commanded PF function. The INV3 adjusts PF function, sets the PF, and can set the ramp. These settings allow the inverter to produce the active and reactive power that is programmed into the V-Q sets. It is noted that, at low power levels, the PF can become undefined. To thoroughly evaluate this function, a variable input should be used to document how closely the commanded PF can be met.

C. TV31 Dynamic Reactive Power Support

This is a commanded function that causes the DER to supply reactive current to the grid during short voltage sags or swells. An out-of-range system voltage can be selected that will cause the DER to disconnect from the EPS in accordance with IEEE 1547 or other applicable safety standards.

D. WP41–42 Watt-Power Factor Function

This function allows the DER output PF to be varied according to the value of the feed-in power from the dc source. Adjustments to this function tend to be long lasting. Therefore, this function is less frequently used.

While all the above-described PF-adjusting functions have slightly different implementations and the results vary slightly, the one similar attribute in all of these PF-adjusting functions is that each affects real power generation levels and negatively affects DER conversion efficiency.

Assessment of Commanded Real and Reactive Power Generation

A photovoltaic utility interconnected inverter is designed to deliver all available real power to the utility and manufacturers continue to optimize the ability to utilize all available dc resources to maximum the kWhs produced and do so reliably to achieve the life cycle cost of energy (LCOE) targets. The high penetration of DER has been shown to have adverse effects on the distribution voltage [6] therefore the requirement for DER to deliver reactive power to minimize this effect is vital for the EPS to continue the high level of performance. Developing the capability to deliver the required reactive power, either it’s commanded or the function is implemented autonomously according to voltage conditions, becomes vital for the high level of implementation to be maintained. Sandia’s Distributed Energy Technologies Laboratory has been investigating the accuracy of real and reactive power delivery under controlled laboratory conditions. The approach is to document the inverters performance under a communicated power command to deliver a specific power level.

Results of INV2—Adjust Maximum Generation Level

The inverter's output power is controlled via Ethernet to modbus communication commands, and the intent of these evaluations it to assess the accuracy of the of the power delivery. The INV2 function sets the real power generation and the inverter sets the real power generation as a percentage of real power rated capacity.

For these tests, the dc source to the inverter is capable of delivering up to 120% of rated output power of the device under test and is held constant, regardless the commanded power level. This is to ensure the output is not curtailed other than by the communicated request. This test is not intended to address the optional ramp time parameter of this function, which defines the time the EUT moves from the current operational value to a new percentage of rated capacity.

The following test results show the inverter responding to communicated power level commands and the data recorded is used to determine the accuracy of the inverter to deliver the requested percentage of rated real power. Figure 2 shows the inverter responding to the power curtailment command. Table 2 shows the accuracy of the inverters ability to deliver the commanded real power.

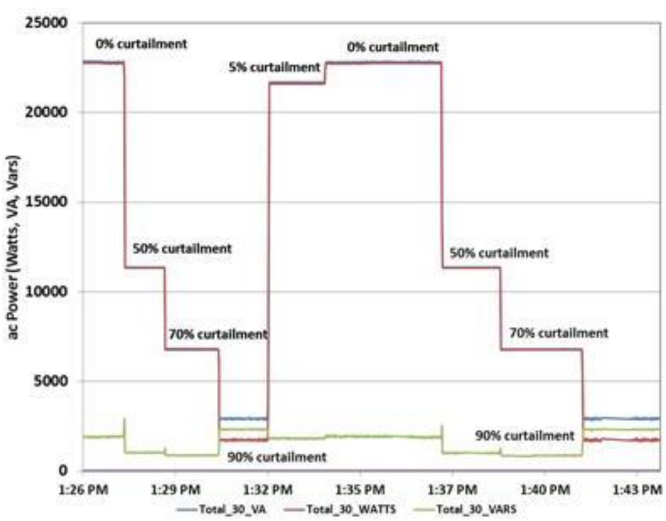

Figure 2: Inverter response to commanded real power

Table 2: Commanded Real Power Accuracy

Power Curtailment	Expected power	Power level	% error
0%	22782	22782	0.00
50%	11391	11328	0.56
70%	6835	6759	1.11

*Results of INV3—Adjust Power Factor*r

The inverter' power factor, i.e., displacement power factor, is also set through communication commands. The advance inverter function used is a VAr priority function (VV12), there the requested reactive power is delivered regardless of real power curtailment. For these tests, the dc source to the inverter is capable of delivering up to 120% of rated out power of the device under test and is held constant, regardless the commanded power level and the inverter is delivering 100% of rated real power. The tests are not intended to address the responsiveness of the communicated commanded but to evaluate the accuracy of reactive power delivery.

The device under test (DUT) produces reactive power as a percentage of real power rating and the following test results show the inverter responding to reactive power commands to inverter. The data presented in Figure 3 displays the responsiveness of the inverter and is used to determine the accuracy of the inverter to deliver the requested percentage of reactive power

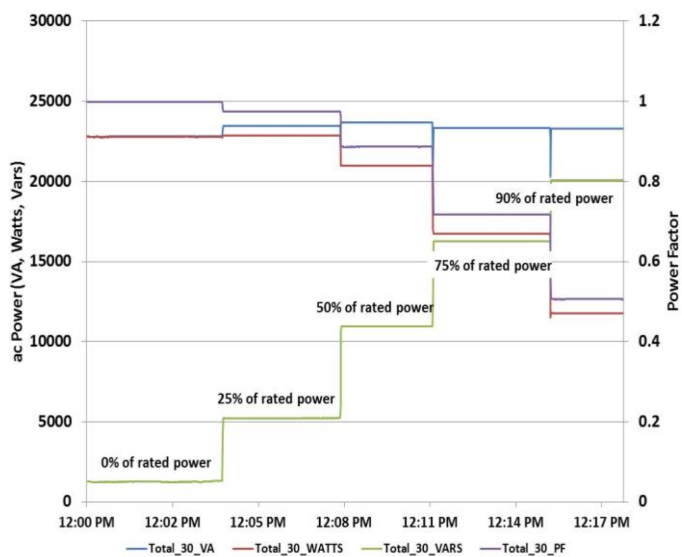

Figure 3: Inverter response to commanded reactive power

Table 3 shows the accuracy of the inverters ability to deliver the commanded reactive power. All reactive power commands over 25% require reduction in real power.

Table 3: Command Reactive Power Accuracy

% of rated	Expected VAr	measured VAr	% error	PF
25	5688.6	5231.8	8.0	0.97
50	11377.6	10967.0	3.6	0.89
75	17067.2	16267.3	4.7	0.72
90	20481.7	20092.1	1.9	0.51

The dc and ac parameters vary under different modes of operations and the VAr priority and the commanded INV3 function may requires the inverters to curtail real power generation to deliver the required reactive power. This typically causes dc voltage to rise and dc currents have higher ripple. The following figures show the increase in dc ripple current when the inverter delivers power at unity power factor and at a power factor of *PF* = 0.5. The increase in dc current ripple is known to have adverse effects [1] on dc link capacitors and the higher dc voltages can contribute to additional switching losses in most applications.

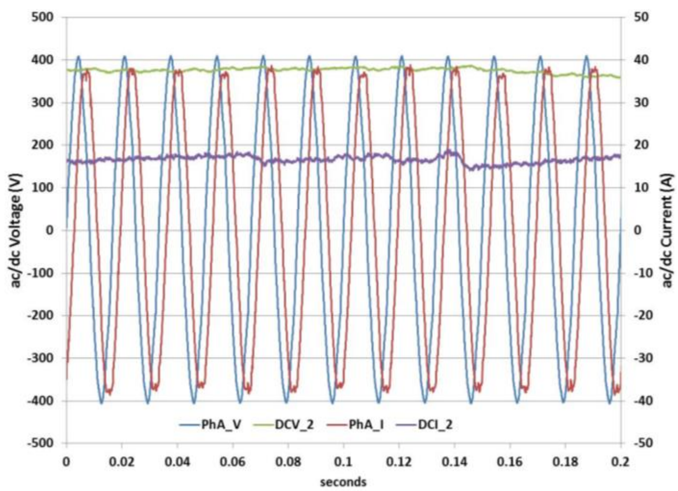

Figure 4: Non-Unity Power Factor ac/dc waveforms

The ac and dc voltage and currents vary considerably during unity and non-unity power factor operation and this variation affect inverter performance including efficiency. Table 4 shows variation in peak-to-peak amplitudes of the dc voltage and currents.

Table 4: Voltage and Current ripple at Unity / Non-Unity PF

Ac/dc Ripple	Unity pf	Non-unity PF
Voltage	5 Vpk-pk	25V pk-pk
Current	1 Apk-pk	5.5 A pk-pk
Voltage mean*	333 V	373 V
Current mean*	35 A	17.3 A

*Operation values

III. Conversion Efficiency and Power Factor

More and more of today's DER devices are expected to deliver reactive power in an effort to participate in voltage regulation or to minimize any negative effect the high penetration of a variable resource may have on EPS stability.

Non-unity PF operation effects on DER devices are most noticeably realized as reduced conversion efficiency. Conditions that contribute to efficiency reduction are

- DC bus conduction losses
- Power electronic conduction losses
- Power electronic switching losses
- Filter conduction losses

When an inverter is operating close to its rated nameplate value and it receives a request to produce reactive power from any one of the identified functions, the inverter will curtail the real power generation to create the reactive power that is requested since the inverter is a kVA-rated device. As a result, the inverter operation will shift to a higher dc voltage on the PV array's IV curve in order to reduce output power (below MPPT). The higher dc voltage may result in lower conversion efficiency and is attributed to higher switching losses because of high dc voltage. Investigating and quantifying the effect reactive power delivery has on conversion efficiency is necessary, since at least four advanced inverter functions require reactive power generation.

A. Power Loss Calculations

A typical three-phase inverter would be constructed using three phase-leg assemblies built using active transistor switched and anti-parallel diodes. For insulated gate bipolar transistor (IGBT)-based inverters, a typical phase-leg configuration is shown in Figure 5 where V_{dc} is the dc bus voltage, i_x may represent phase currents i_a , i_b or i_c , r_x is the phase circuit resistance in Ohms, r_{dc} is the dc bus conductor resistance in Ohms and r_C is the dc link capacitor equivalent series resistance in Ohms.

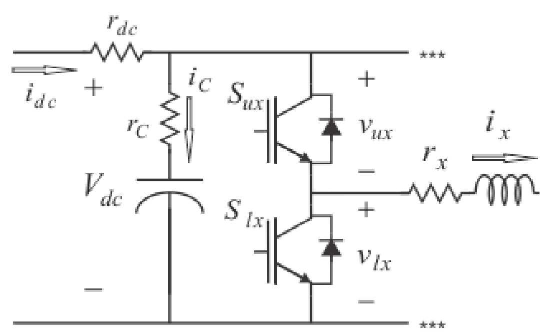

Figure 5: Schematic showing typical inverter phase leg

The power losses may be modeled as the sum of switching losses and conduction losses. It is common to model the conduction loss by considering the forward voltage drop v_F of the component as the sum of a constant value and an equivalent resistance value, given as

$$v_{Ft} = a_t i_t + b_t \tag{1}$$

$$v_{Fd} = a_d i_d + b_d \tag{2}$$

where v_{Ft} is the voltage drop of the transistor and v_{Fd} is the voltage drop of the diode, a_t , a_d have units of Ohms and b_t ,

b_d have units of Volts. The currents i_t, i_d will depend on the conduction state of the device and the value of i_x.

To compute the switching loss, it is convenient to compute the energy lost during the *turn-on* and *turn-off* transitions of each device and multiply this by the switching frequency. Assuming a linear transition in both the current and voltage during each switching event and neglecting the small forward voltage drop during conduction, estimates for the turn-on and turn-off energy losses, for $i_x > 0$, are computed as follows for the upper transistor switch

$$E_{Sux,Ton} \approx \int_{t}^{t+T_{on}} \left(V_{dc} \frac{T_{on} - \tau}{T_{on}} \cdot i_x \frac{(\tau - t)}{T_{on}} \right) d\tau = \frac{1}{6} V_{dc} i_x T_{on} \quad (3)$$

$$E_{Sux,Toff} \approx \int_{t}^{t+T_{off}} \left(V_{dc} \frac{(\tau - t)}{T_{off}} \cdot i_x \frac{T_{off} - \tau}{T_{off}} \right) d\tau = \frac{1}{6} V_{dc} i_x T_{off} \quad (4)$$

where T_{on}, T_{off} are the turn-on and turn-off times in seconds and are assumed constant in this expression. Thus, for example, for $i_x > 0$ and a duty cycle of d_{ux} the average value losses in the top switch S_{ux} may be modeled as

$$P_{Sux,loss} \approx d_{ux}\left(a i_x^2 + b i_x\right) + \frac{1}{6} f_{sw} V_{dc} i_x \left(T_{on} + T_{off}\right) \quad (5)$$

where f_{sw} is the switching frequency in Hertz.

Higher fidelity models have been developed and demonstrated in the literature. In [8], behavioral models to characterize conduction losses and switching losses in IGBT's and diodes are presented. The authors developed their models empirically by performing careful measurements of the device losses at different voltage and current levels while being held at a given temperature and fitting these results to a curve. The results included nonlinear expressions for the transistor and diode forward voltage drops as well as for the turn-on and turn-off times.

The losses in the phase conductor are modeled only as conduction loss

$$P_{filt,loss} = r_x i_x^2 \quad (6)$$

Likewise, the conduction losses in the dc bus and dc link capacitor are similarly given as

$$P_{dcbus,loss} = r_{dc} i_{dc}^2 \quad (7)$$

$$P_{C,loss} = r_C i_C^2 \quad (8)$$

In general, inverter losses tend to rise as PF drops due to several mechanisms including: conduction (I^2R) losses, IGBT switching losses, additional current flowing through the inverters' antiparallel diodes (these typically have higher losses), and higher ripple through parasitic series resistances in dc filter elements.

If one were to model each loss mechanism and sum the losses, it should be possible to attain an accurate result. However, given the difficulty in accounting for each mechanism, it is convenient to consider the development of an empirical model, similar to what was done in [8] at the device level, except the model would be applied to a whole inverter. As an example, an empirically derived loss model was developed for a single experiment. Specifically, a 25 kVA three-phase inverter was supplied by a PV emulator and evaluated at several PF levels. The inverter was allowed first to 'warm up' and then operated with a variable irradiance profile and PF levels of 0.5, 0.72, 0.87 and 0.97. The dc voltage was allowed to vary about a mean value of about 350 Vdc. The data was then fit to the following expression

$$P_{loss} = K_I I_{RMS} \left(\frac{V_{dcB}}{V_{dc}} \right) + K_{PF} PF + K_b \quad (9)$$

where P_{loss} is the power loss in Watts for the entire inverter, K_I is a interpolation term in Volts (i.e. Watts/Amp), I_{RMS} is the average RMS phase current of the three phases, V_{dcB} is the 'base dc link voltage' in Volts, K_{PF} is an interpolation term in Watts and K_b is a bias term in Watts. The expression was determined through trial and error and is not expected to be unique. Using over 1000 data points, a nonlinear least squares method was applied to determine the interpolation and bias values used in (9). These values are given in Table 5. The data points were then compared to the values attained through interpolation. The result was a good fit to the data with a mean error of just 5.35%. The comparison is also plotted in Figure 6.

Table 5: Values used in Equation (9)

Parameter	Value
K_I	45.28 V
K_{PF}	-883.3 W
K_b	137.9 W
V_{dcB}	350 Vdc

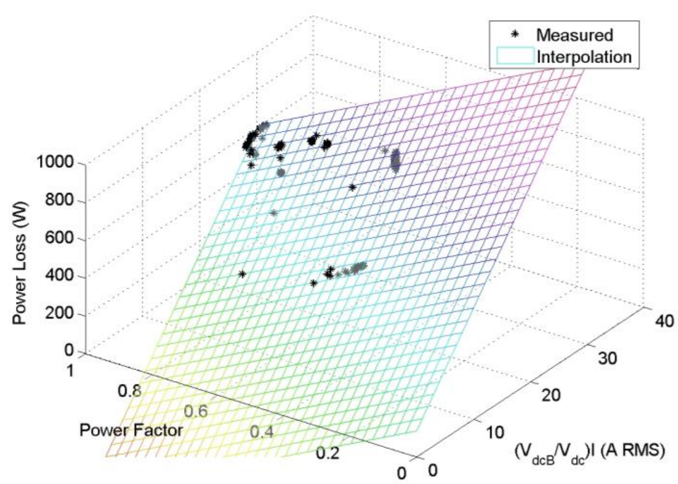

Figure. 6: Comparison of power loss data to empirical model

B. Method to Calculate Efficiency

PV inverter conversion efficiency is determined using a procedure well described in the California Energy Commission CEC Inverter Performance Test Protocol [1]. The calculations involve six power levels and three dc voltage levels while the inverter is operating at approximately unity PF. Presently an effort is under way to augment this test procedure that will include efficiency calculations with the device under test operating at non-unity PF. Sandia National Laboratories' Distributed Energy Technologies Laboratory has conducted experiments to investigate the effects of non-unity PF operation on inverter efficiency. The two most influential parameters on conversion efficiency are dc voltage and power level. Figure 7 shows the effect on inverter efficiency as PF changes with voltage held constant.

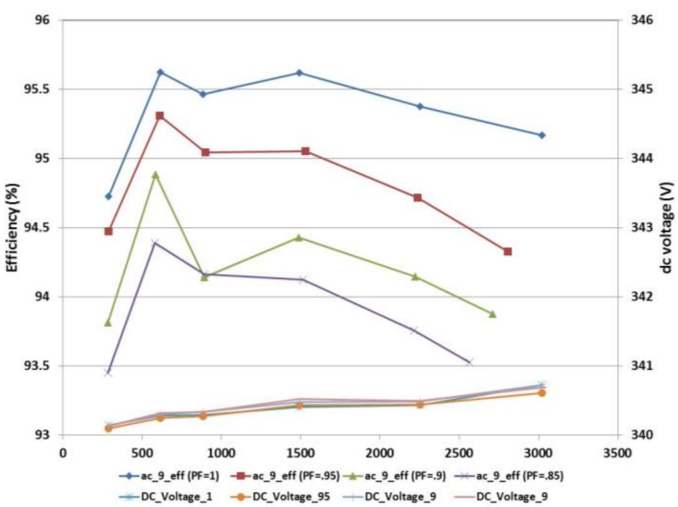

Figure. 7. Conversion efficiency at different PFs.

The assessments conducted on inverter's efficiency during unity and non-unity power operation has shown to vary considerably among different inverter topologies. Figure 7 shows how the inverter's efficiency varies with decreasing power factor.

IV. Conclusions

In this paper, non-unity PF advanced inverter functions were identified and the effects these advanced inverter functions have on the performance of the inverter and the ability for hardware to meet the programmed real and reactive power levels were assessed. Results demonstrated that non-unity PF decreases conversion efficiency. Several loss mechanisms were discussed and the complexity of summing the different loss mechanisms was noted. As an alternative, a method for interpolating inverter loss was presented with results from one experiment. The interpolation approach is empirical but can yield accurate results.

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