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Robert H. Josephs

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ABSTRACT

This study describes the design and estimates the performance of a modestly sized utility-connected power conditioning system and its supporting photovoltaic collector. The system will power special loads at JPL, Pasadena, California. The study also examines utility preparations and investigates how well guidelines have been developed to commingle the output of a small generating station with that of a large power network. The small photovoltaic system will provide a capability to study means to have an electrical power generator for small scale application conform with the necessarily inflexible organization of the community-sized power generating plant and distribution grid.

No electrical storage is planned for the 10 kVA photovoltaic system and no surplus power is expected at the initial stage. Power is drawn from the utility when the array falls short of the load demand. The solar modules, numbering 315, are pedestal mounted at ground level with fixed orientation. Single phase power at 240 volts AC is supplied to the loads by the power conditioning equipment that will provide about 15% of the load demand. This design facilitates system scale-up to 30 kVA that can supply 42% of the load requirement with significant surplus power returned to the net.

ACKNOWLEDGEMENT

The author acknowledges the effort of Dr. Ta-Jin Kuo in his preparation of an earlier version of this work, and is grateful for the contributions of T.A. Casad, Dr. Radhe Das, M.F. Hanna, W.A. Hasbach and the JPL Facilities Engineering and Construction Section.

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1.0 INTRODUCTION

The promise of terrestrial photovoltaically generated electrical power will be realized when many small facilities connect to utility power grids. However, important answers are first required regarding the readiness of utilities to properly operate with many dispersed co-generators, regarding the status of the technology to convert the solar array DC output to the quality AC power that is required by the utility, and regarding the reliability of solar arrays and their ability to match performance to specifications.

Electrical utilities have refined their technology for decades and have developed a cooperative power network, conservatively managed and generally reflective of modern technology. Despite their technical sophistication, power utilities are still vulnerable to disturbances that precipitated memorable recent widespread electrical blackouts. Disturbances can become more frequent with large numbers of small co-generating stations dispersed upon utility grids. Not having to consider strangers before, utilities are just beginning to assess the consequence of their presence and the problems of interoperability.

The power conditioning electronics of a photovoltaic system has to contend with a very variable energy supplier in the solar array and a utility with stringent requirements, and to manage using electronics of a new generation not yet fully developed.

An attempt to integrate it all - array, conditioning and control electronics, and the utility, reveals poorly defined and challenging interfaces. The purposes of this study are to review some of the interfaces and to present a modest utility connected photovoltaic system design that can be used to explore means to strengthen the dispersed electrical co-generator and electrical utility symbiotic tie.

The NASA/JPL interagency agreement with DOE for this investigation states that the design and analysis study, will fulfill the following:

- A power system design to include the evaluation of newly available high efficiency inverters
- Fabrication plans for the power subsystem and an implementation plan for the demonstration of a utility connected photovoltaic unit.
- Cost analysis for the installation and operation of the system.

Components of the PV system will be of proven and reliable designs, and it is intended that the system meet the key provisions of the Federal Photovoltaic Utilization Program (FPUP) (1) to:

- Provide technological feed-back to the DOE photovoltaic technology development program based on experience gained through fielding photovoltaic systems.
- Gain early experience in environmental and institutional issues for systems in a variety of applications.
- Develop a life-cycle cost methodology appropriate for use with a wide variety of photovoltaic systems and alternatives, and encourage the use of this cost evaluation tool within the Federal establishment.

The purpose of the Federal Photovoltaic Utilization Program is to (1):

- Accelerate the growth of a commercially viable and competitive industry to make photovoltaic solar electric systems available to the general public as an option in order to reduce national consumption of fossil fuel;
- Reduce fossil fuel costs to the Federal Government;
- Stimulate the general use within the Federal Government of methods for the minimization of life-cycle costs; and
- Develop performance data on the program.

2.0 System Requirements

For the purpose of this study, some electrical loads were selected at adjacent JPL buildings to be powered by a photovoltaic system operating in parallel with the Southern California Edison (SCE) utility. Because of increased costs and system complexity, battery storage and battery recharge capability were considered more a burden to this study than contributor of future design information. That portion of the electrical load not supplied by the array is to be provided by the utility, and no surplus array power for utility purchase is anticipated at the initial design scale. The electrical loads are among those at the JPL First Aid and Fire Stations, and electrical cables to the loads are to be routed to a special bus that is jointly powered by the PV station and SCE.

2.1 Load Profile

Electrical loads in the JPL First Aid Station and Fire Station buildings that were selected to be powered are listed in Table 1. To assess duty cycles, strip chart recordings were made of clamp-on ammeter readings on the power leads to the refrigerators and water heater. Nighttime loads for both stations totaled 10.4 kW, the daily average peak loads amounted to 19.4 kW and the average daily power consumption totaled 347.4 kWh. The resulting power profile shown in Figure 1 is a straight line average of the total electrical loads, including the duty cycles recorded on the strip charts.

2.2 Overview

Figure 2 is a block diagram of the solar array, power conditioning equipment (PCE), utility grid interface and load bus configuration to support the load power profile. The flat plate array is rated at 10 kW peak output. The PCE, a 10 kVA unit, incorporates various automatic controls for the array, the system and at the interface to the utility, in addition to converting the array DC output power to the AC power specified for the load and for the utility power net.

	Watts	
Refrigerators		
Fire Station	250	
Squad Room	650	
First Aid Station	650	
		1,650
Water Heater		
First Aid Station		4,500
Sterilizer		
First Aid Station (weekly)		1,500
Lighting		
Fire House	1,032	
Fire Station and Squad Room	8,364	
First Aid Station	8,364	
		17,760
	TOTAL	25,410

Table 1. JPL Station Electrical Loads to be Powered by a Utility Connected Photovoltaic System

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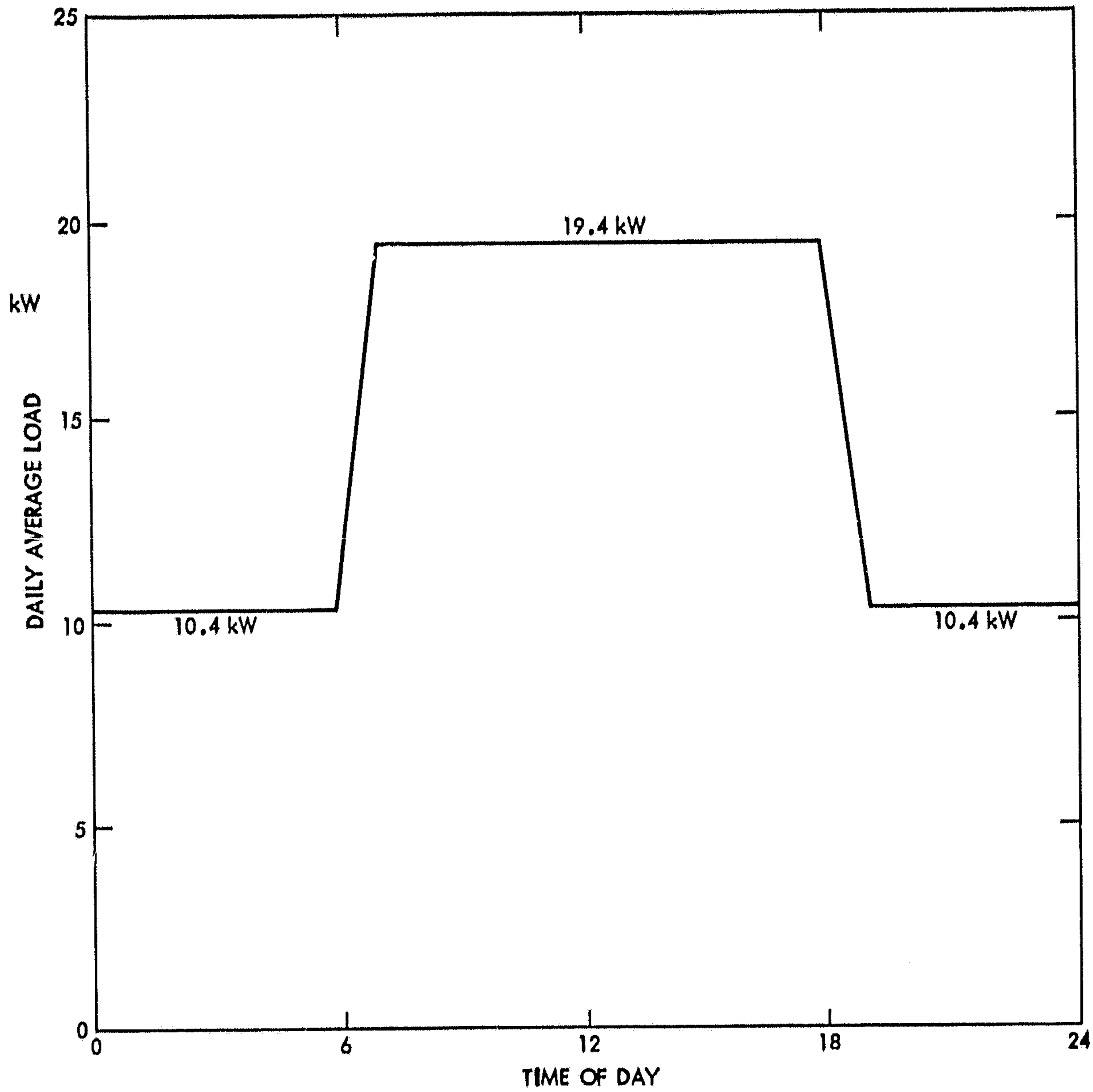

Figure 1. The Daily Average Load Profile of the Special Loads in the JPL First Aid and Fire Stations. The Average Daily Power Consumption is 347.4 kWh.

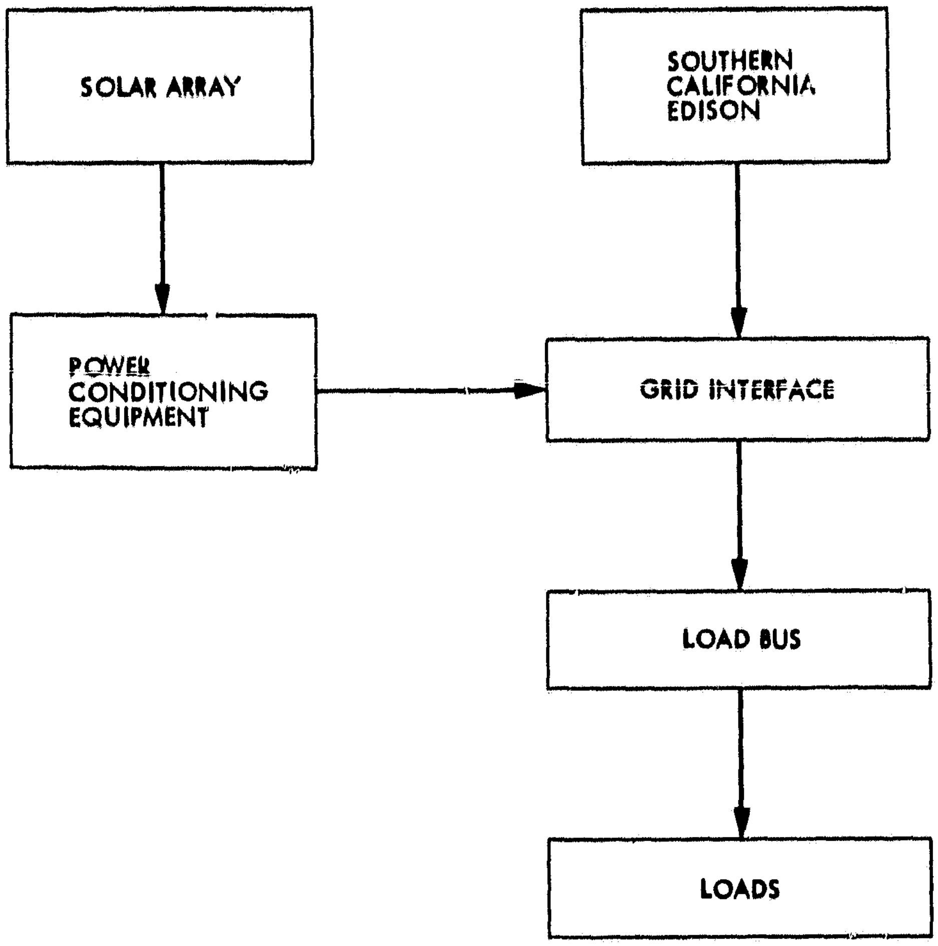

Figure 2. Block Diagram of the JPL Utility Connected Photovoltaic System.

2.3 General Utility Interface Requirements

A review was made of existing utility requirements for small co-generators that are connected to the utility power distribution grid, and extended to a review of network operational parameters and utility procedures that could impact the operation of the small systems. The information was initially directed to the design of the JPL PV system and for the selection of suitable power conditioning equipment and instruments. Later, the information will apply to expedite the PV system connection to the grid, and it will aid to organize appropriate operational procedures to conform to specific utility requirements and as an information base with which to operate the PV system in a knowledgeable manner.

2.3.1 Voltage Regulation and Reactive Load Compensation

An electrical power utility tries to maintain voltage specifications at customer terminals throughout its system despite variations in load magnitudes or the proximity of a user to a substation. To facilitate power distribution, utilities generally allocate the highest voltage of the specified voltage range to the first or nearest customer to the substation and reserve the lowest specified voltage for the last customer on the grid; see Figure 3. Usually stable adjustments are set on variable tap transformers, induction and step regulators and on shunt and series capacitors, to control the flow of reactive power throughout the grid. Reactive power flow, I^2R losses and voltage magnitudes are readily determined when power is radially distributed from a substation in a singly directed outflow.

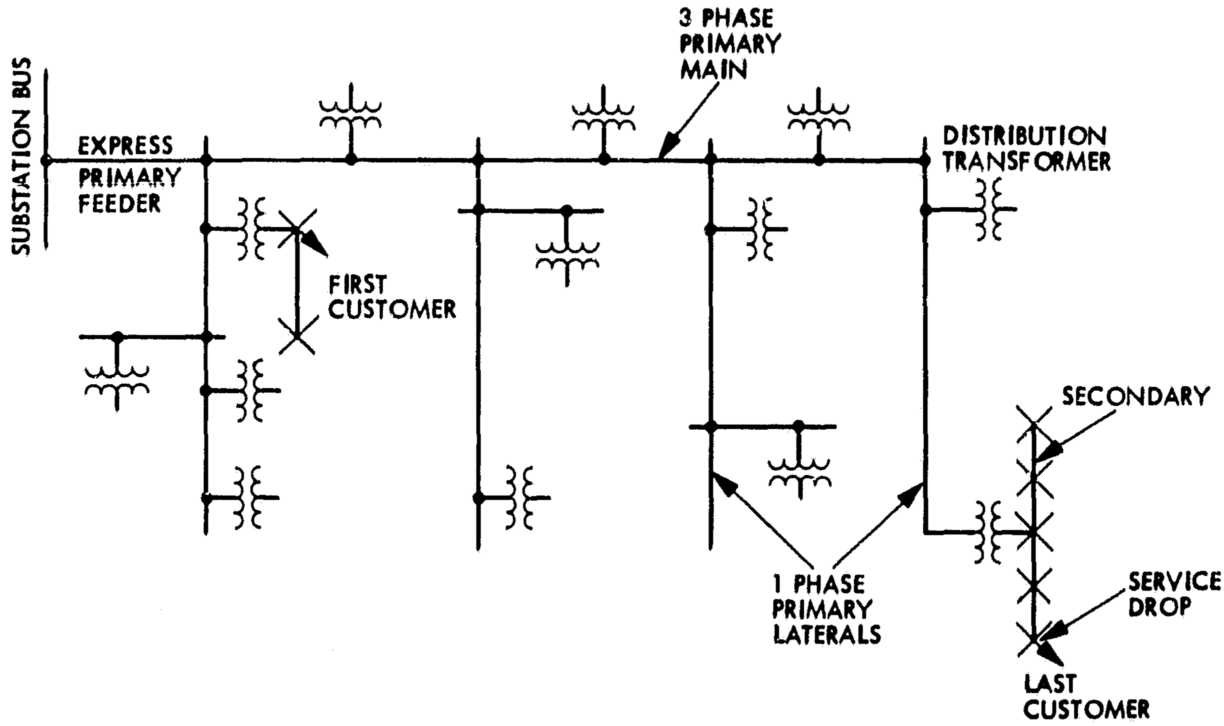

Figure 3. Feeder Components and Location of First and Last Customer. (2)

Analyses are more complex with power generators at customer sites distributed on the grid. A formerly last customer with a grid-connected PV system would effectively be promoted to a closer proximity to the substation. Should he generate surplus power it becomes uncertain which customer is first or last at a given moment, considering load and solar array output variations. The typically stable settings for reactive power distribution would probably be replaced by more dynamic adjustments for efficient power management. Computers may best allocate impedances to maintain specified voltage regulation on a grid with many PV co-generators during a partly cloudy day.

DC-AC converters that are line commutated operate at lagging power factors and draw reactive voltamperes (VARs) that are supplied by the utility. The utility also supplies VARs as required by the PV system loads, while the PV system supplies the real power (kW) demand of the loads. During periods of high insolation, the PV system supports a greater share of the real power demand and the utility supplies less real power and a greater portion of reactive power. Since real power is usually metered by utilities, supplying a higher ratio of VARs to real power results in a utility revenue loss. At present there is little information to guide a PV system owner regarding the magnitude of reactive power he would be permitted to generate or consume.

A high ratio of VARs to watts on the net also causes voltage regulation difficulties at the substation that are generally relieved by switching power factor correcting capacitors into the system as needed during periods of high insolation. These must be switched out at periods of low insolation if overvoltages are to be avoided. Utilities could charge for VARs used in PV systems, but it may prove more economical for line commutated converters operating at lagging power factors to use capacitors to correct the power factors than to have the utility supply and charge for VARs' service. It must be applied cautiously however, since power factor correcting capacitance can cause undesirable resonances as it reacts with system harmonics.

The non-sinusoidal operation of modern inverters give rise to reactive volt amperes with complex components that have uncertain impact upon regulation of the utility voltage. Conventional instruments can't be used for non-sinusoidal VARs' measurement. Special instrumentation is required to subdivide each non-sinusoidal current component with respect to the voltage waveform in order to measure the component's corresponding power magnitude.

2.3.2 Harmonics

Utility power grids receive undesirable current and voltage harmonics that are produced during DC to AC power conversion. Harmonic magnitudes at different frequencies imposed on the utility power waveform are functions of the DC/AC converter characteristics and of the system impedance at the point of grid interconnection. In addition to the characteristic harmonics produced by ideally operating converters, harmonics are also the product of unbalanced line voltages, of noise in electronic switching circuits, and of interactions of the characteristic harmonics and the fundamental currents in non-linear portions of the system.

Excessive line harmonics can be undesirable for the following reasons:

- Overheating. Lower impedance to higher order current harmonics can cause overheating in rotating machines, transformers and capacitor banks.
- Interference. Current harmonics cause interference with voice communication on telephone lines.
- Relays. They cause protective relays to malfunction.
- Metering. Harmonics can cause real and reactive power to meter erroneously.

- Equipment. Equipment can malfunction because of sensitivity to line harmonics; computers particularly.

A customer with a utility connected PV co-generator is obligated not to disturb or degrade the quality of the existing grid power to the detriment of other users. Owners of PV systems producing excessive harmonics may be required to install additional filtering to reduce to acceptable levels the harmonic content of their systems, or shut down. SCE has no harmonic specification at present so that their harmonic surveillance is largely based upon user complaint.

The undesirable effects of excessive harmonics are better understood than apparently the means at present to develop adequate specifications to limit their generation in distributed co-generation systems. Instituting a harmonic standard is a complex procedure involving transmission line theory to establish the maximum allowable harmonic limits at points on the grid, and to consequently determine the maximum allowable current or voltage harmonics at the output of the PCE. The harmonic limit would depend upon the characteristics of the distribution system and its background harmonic level. Evaluating the harmonic content of the output waveform of the converter requires special equipment expertly used. Should a PV system owner be required to rectify a harmonic insertion problem, the design of the filters employed must consider the grid network impedance at various harmonic frequencies at the system connection point.

2.3.3 System Unbalance

Unequal loading on various phases of three phase systems contribute to system unbalance. Unequal current and voltage in the three phases cause propagation of triplet harmonics (frequency multiples of three) on the lines that are otherwise cancelled in a balanced operation. The consequence could be nuisance tripping of protective devices, voltage regulation error, and equipment overheating. Unbalanced phased voltages applied to three-phase motors cause excessive negative sequence currents that overheat the units. Studies (2) indicated such motors operating near full load overheat with phase voltage unbalance exceeding 2 percent. Some electronic equipment, computers particularly, perform poorly under unbalanced conditions.

With PV generators connected to the net, it may be difficult for the utility to maintain desirable balance since typical smaller PV systems are expected to be single phase connected to one of the three phases, as is the system for this study, and it is unlikely that at a given time the load magnitude of each phase will be uniform. Having sensitive three-phase equipment connected to dedicated three-phase circuits free of single phase supplies may be a recommended procedure in the future.

Unbalance in voltages to neutral of a single-phase, three-wire system is determined (3) by

$$\frac{|V_2|}{|V_1|} = \frac{|V_{1N}| - |V_{2N}|}{\frac{V_{1-2}}{2}} \quad , \text{ when } |V_{1N}| > |V_{2N}|$$

where:

V_{1N} and V_{2N} = rms voltage to neutral of lines 1 and 2

V_{1-2} = normal rms line-to-line voltage

Unbalance in a three-phase, three wire system in which the zero sequence voltages are zero is given by:

$$\frac{|V2|}{|V1|} = \left[\frac{\dfrac{a^2 + b^2 + c^2}{6} - 2\left[\dfrac{s(s-a)(s-b)(s-c)}{3}\right]^{1/2}}{\dfrac{a^2 + b^2 + c^3}{6} + 2\left[\dfrac{s(s-a)(s-b)(s-c)}{3}\right]^{1/2}} \right]^{1/2}$$

where:

V_1 = positive sequence voltage

V_2 = negative sequence voltage

a, b, c = the absolute values of respective line-to-line rms voltages

$$s = \frac{a + b + c}{2}$$

Although the mathematical procedure to determine voltage unbalance is established, there may be difficulty in obtaining a coherent set of voltage parameters with which to make the calculations.

2.3.4 Stability

PCE systems with improper controls that adversely respond to a disturbance by outputting power with large fluctuations of voltage, current and frequency are said to be unstable.

Unstable operation can cause nuisance tripping of protective devices in the PV system. Its effect could be widespread causing tripping of substation breakers, and beyond, since the effects of instability propagate and are the main ingredient of large area blackouts. In addition, customer or utility equipment could be damaged, and the process of finding the fault, rectifying it and reconnecting the substation and distributed systems back on net could be a protracted and costly inconvenience.

The PCE incorporates control loops to maintain operational parameters such as those controlling current, voltage and frequency. The optional solar array maximum power point tracker, discussed later, is another type of control loop. Transfer functions of the various elements of control loop circuitry determine the overall stability of the PV system. Unstable or marginally stable performance after a disturbance may require control system adjustment or modification.

Not much is known at the present (4) about the impact of PV system instability on the net, or about the possible dynamic interactions among other PV systems or other types of distributed generators connected to the net that could contribute to or reinforce instability.

2.3.5 Protection

Guidelines presently available for protective measures to be taken by owners of PV generating stations are general in nature and are mostly protective of the utility that requires protection against over-voltage, over-current and over- or under-frequency, transients and other abnormal conditions that could originate in the PV system and affect the power grid. Apparently no guidelines are available to protect the PCE from utility generated abnormal conditions.

It is not unusual to specify surge-withstand voltage levels in PCE electronics that are 10 to 20 times normal voltage for electrical components (switches, cables, transformers, etc). It is impractical to achieve similar withstand levels for small electronic components (transistors, diodes, SCRs, etc.), or integrated circuits, and appropriate voltage surge protection is necessary to prevent damage to these components in the PCE.

It will largely be the responsibility of PV system owners to prevent damage to their system by line overvoltage or undervoltage, and also to protect the utility from similar operational abnormalities arising from their own system. The magnitude of transient overvoltages or surges that occur on utility nets as a consequence of nearby lightning strikes depends on the point of strike impact and system characteristic impedance. One method to protect hardware from lightning-induced current surges is to employ varistors in the array positive and negative output leads, with the varistors connected to ground. Direct lightning-strike protection for the array is not a requirement at present. Transients on the net are also caused by switching and restrikes of switches and circuit breakers.

Voltage rise as much as 1000 kV per microsecond is possible on overhead distribution systems as a result of a severe nearby lightning strike, and it is not unusual for a utility short circuit current to reach 10,000 amps for a very short time.[2] Accordingly, PV systems can become a hazard unless fault detectors function and the equipment disconnects as a consequence of fault overcurrent. Residential circuits are exposed to voltage surges of about 2-5 kV on utility nets, while the wiring breakdown limit is typically 6-8 kV. For acceptable reliability, a study[2] recommends that the PCE withstand the same surge level as the wiring.

Because typical solar array I-V characteristics limit current within 20% above operating levels, PV systems would be a weak source of fault current to a utility, probably under 100 amps, and fault current sourced at dispersed PV generators is not expected to strain present utility overcurrent protective devices.

However, it is important that the PCE be capable of regulating nominal output voltage no more than ± 3% to prevent over or undervoltage from entering the utility grid, a condition that can damage or shorten the life of user equipment. Controls should isolate the inverter from the net should the utility voltage drop 20%. Special controls are required to synchronize the PV system to the utility whenever the two systems connect.

It is desirable to fully understand the PV system design and operational procedures to protect the PV system from anomalous performance originating within itself before implementing device design and operation strategies to protect the PV system from anomalies originating on the net. The specifics of anomalies originating on the net must be fully understood as well. Unfortunately, not much is known of either, or the manner each impacts the other at the present state of technology development, and one of the purposes of organizing PV system-utility interfaces is to gain this information.

2.3.6 Safety

It is anticipated that revisions to the National Electrical Code (NEC) that is published by the National Fire Protection Association every three years will include recommendations for photovoltaic generating installations. The 1981 edition does not. There have been few investigations on safety for PV systems to date.[4] The NEC is the prime set of guidelines to assure safe installation of residential, commercial and industrial electrical systems. Some points for consideration:

Utility Disconnect Should the utility suffer a power loss, it is desirable to have photovoltaic systems automatically disconnect from the power net. This procedure isolates the dispersed photovoltaic generating units to safeguard utility repair personnel. At a minimum, utility employees should have unrestricted access without notice to an isolating disconnect device incorporated in the control hardware complement of a PV installation, to operate and to lock the device electrically open. A remote switching station disconnecting a group of PV generators may be a more practical solution with many dispersed installations. Electrical isolation requires all lines including neutral to be switched open.

2.3.7 Grounding

It has been recommended (2) that only the inverter chassis be connected to AC ground, and that an isolation transformer be used to couple the inverter output to the utility power system. The procedure permits the solar array to be electrically grounded at any voltage point, and it prevents the possibility of a voltage excursion of an array virtual ground with respect to true earth ground from being injected into the power net. Little is known or documented at present about DC injecting into the grid. (5)

2.3.8 Transformer

Most utilities require a dedicated distribution transformer for dispersed generators about 5 kVA and above in size, but it is uncertain whether reference is made to an isolation transformer or something in addition. (5) It is also suggested that power line poles or the dedicated transformer unit be conspicuously tagged to alert crews of a possible backfeed.

2.3.9 Metering

The induction disk type meters in wide use generally record only the fundamental component of the total real power (kWh) of electrical consumption. Metering will require modification if the exchange of power between the PV system and the utility is to be accurately measured for billing purposes. Some considerations are: (2)

1. One Meter. One bi-directional kilowatt-hour meter could be used to record the net amount of energy consumed from or delivered to the net by the PV station. Utility buy-back and selling rates would have to be the same and no time-of-day metering employed.

2. Two Meters. Using a separate meter to record the energy delivered by the utility and the energy delivered to the utility lifts restrictions on buy-back rates.

3. Clock Recording. The utility could impose a schedule of rates based upon time-of-day use, the most expensive metering option.

4. Three Meters. Should an adverse power factor of a PV station cause concern to the utility, a meter to measure the net VARh consumed could be used, although no standard definition exists at present for non-sinusoidal VARs.

The non-sinusoidal wave distortion expected in co-generator systems renders inaccurate the meters presently in use and new electronic designs are under investigation. (2) Also, limited knowledge exists of the impact of line harmonics on the performance of present metering. (4)

3.0 Power System Design

The photovoltaic system to support the JPL station's power profile in Figure 1 consists of a nominally 10 kW flat plate solar array collector. The collector area is 115.3 m^2 to be oriented at a fixed 34° tilt angle to horizontal. A 10 kVA power inverter converts the direct current output of the array to the alternating current used by the loads, and the power conditioning equipment interfaces with the power utility to draw power whenever the PV output falls short of the load demand. The PCE also functions to condition the AC power to meet load and utility requirements, to start and stop the operation of the system, to synchronize the generated AC power with that of the network, and to protect the utility network from abnormalities generated at the PV station and also to protect the PV station from net abnormalities.

3.1 Solar Array

The module for this study is rated at 34 watts peak power at 1 kW/m^2 insolation that results in a nominal operating cell temperature (NOCT) of 52°C. Voltage at maximum power at these conditions is 16.0 volts. A solar array consisting of 315 of these modules would have a peak output of about 10.7 kW with no losses considered. However, a total allowance of 5% is made for losses that occur in interconnecting the modules, for the circuit mismatch loss due to slight differences in module electrical characteristics and for the loss incurred in the 245 meter cable run from the array to the PCE. After considering losses, the resulting peak array output at 1 kW/m^2 insolation at NOCT is slightly above 10 kW at the input to the inverter (see Figure 8). This figure shows the estimated solar array I-V characteristics at temperatures of 0°C, 28°C, and 52°C (NOCT) when the sun insolation is 1 kW/m^2. An estimated power-voltage characteristic is also shown for the array operating at 52°C.

The NOCT parameter is usually available in array product literature and is to some extent fixed for a manufacturer, but the conditions under which NOCT is determined are not standardized. NOCT is a property that is largely based upon the module capability for rejecting thermal energy and is the consequence of cell physics, cell packing density, encapsulants, module frame, etc. The NOCT shown in this report is typical of modules marketed at present.

The module measures 0.3 m x 1.22 m (1 ft x 4 ft), for an area of 0.366 m^2. Seen at the inverter, the efficiency of the array is about 8.8% operating normal to the sun whose intensity is 1 kW/m^2, and at the NOCT of 52°C. The system operation requires a module circuit arrangement of 15 modules electrically connected in series with 21 modules in parallel, as shown in Figure 4. A blocking diode is placed in each module series string to prevent reverse current flow should a module suffer a voltage decline or short.

3.2 Array Tilt

The array for this installation will be installed facing south at the fixed angle of 34° from horizontal in an effort to reduce structural fabrication and installation costs, and to reduce maintenance costs for periodic array reorientation. Studies have shown that an array adjusted to a tilt angle from horizontal equivalent to the latitude of the locale most effectively optimizes sun acquisition throughout the year for an array installation of fixed orientation.

3.3 Array Site

The electrical load magnitude to be supported by the PV system is modest in size, and an unshaded sloped roof facing south offers an optimum array site. Some 100 square meters of rooftop are required for a 10 kW system and the roof area is put to good utility without having to sacrifice use of costly adjacent land area.

Occasional strong local winds prevent similar installation on the roof of one of the JPL Stations. Structural reinforcement would be required for the roof to withstand estimated worst-case local wind load stresses imparted by the array. Using an available land site for the array that is located

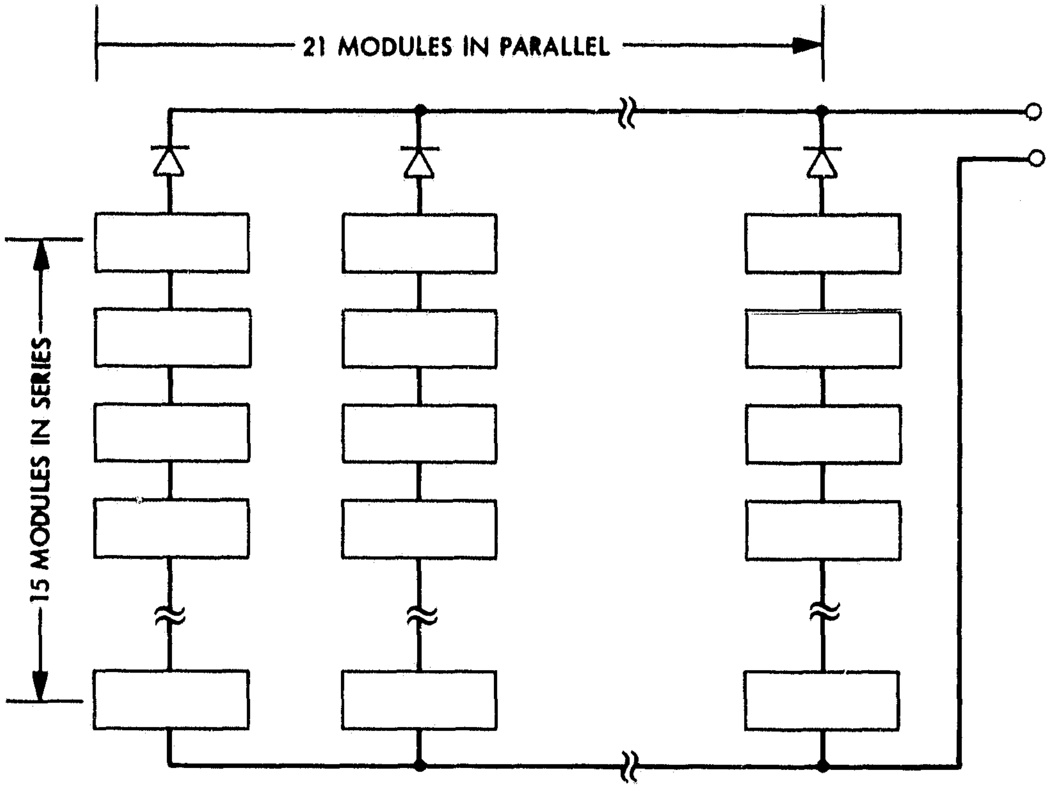

Figure 4. JPL Solar Array Circuit Configuration

near the JPL buildings results in a more economical installation despite increased cabling cost. The site area, shown in Figure 5, allows for possible array expansion to 30 kW. The area is free of shading from flora or structures and there are no nearby homeowners at elevated locations who could consider objectionable the sun reflection from the array. About 240 meters apart, the array site and PCE can be connected either by overhead or underground cable.

For the JPL installation:

1. Power lines will be enclosed in grounded conduits.
2. Mounted instruments will be housed in totally enclosed grounded structures.
3. Ground fault interrupters will be installed.
4. Manually actuated disconnect switches will be installed at the array output bus, at the inverter input and output and at the dedicated distribution transformers.
5. The solar array site will be protected by a six foot fence.
6. Warning signs will be posted to alert maintenance personnel of a utility-connected photovoltaic co-generator.

3.4 Array Support Structure

In a program to develop reliable inexpensive array structural supports [6], a treated wood truss with a wooden base was found capable of supporting twice the array load that is typically required, at almost half the cost of a similarly sized steel-concrete structure, and it is this wooden construction that is recommended for the JPL installation.

The structure, illustrated in Figure 6, consists of 10 cm x 10 cm (4 in x 4 in) end truss members that support an aluminum frame into which the modules are fastened. The base of the truss is a plywood member, reinforced as shown. A trench is dug for the truss base to a depth of 1.07 meters (3.5 feet), and

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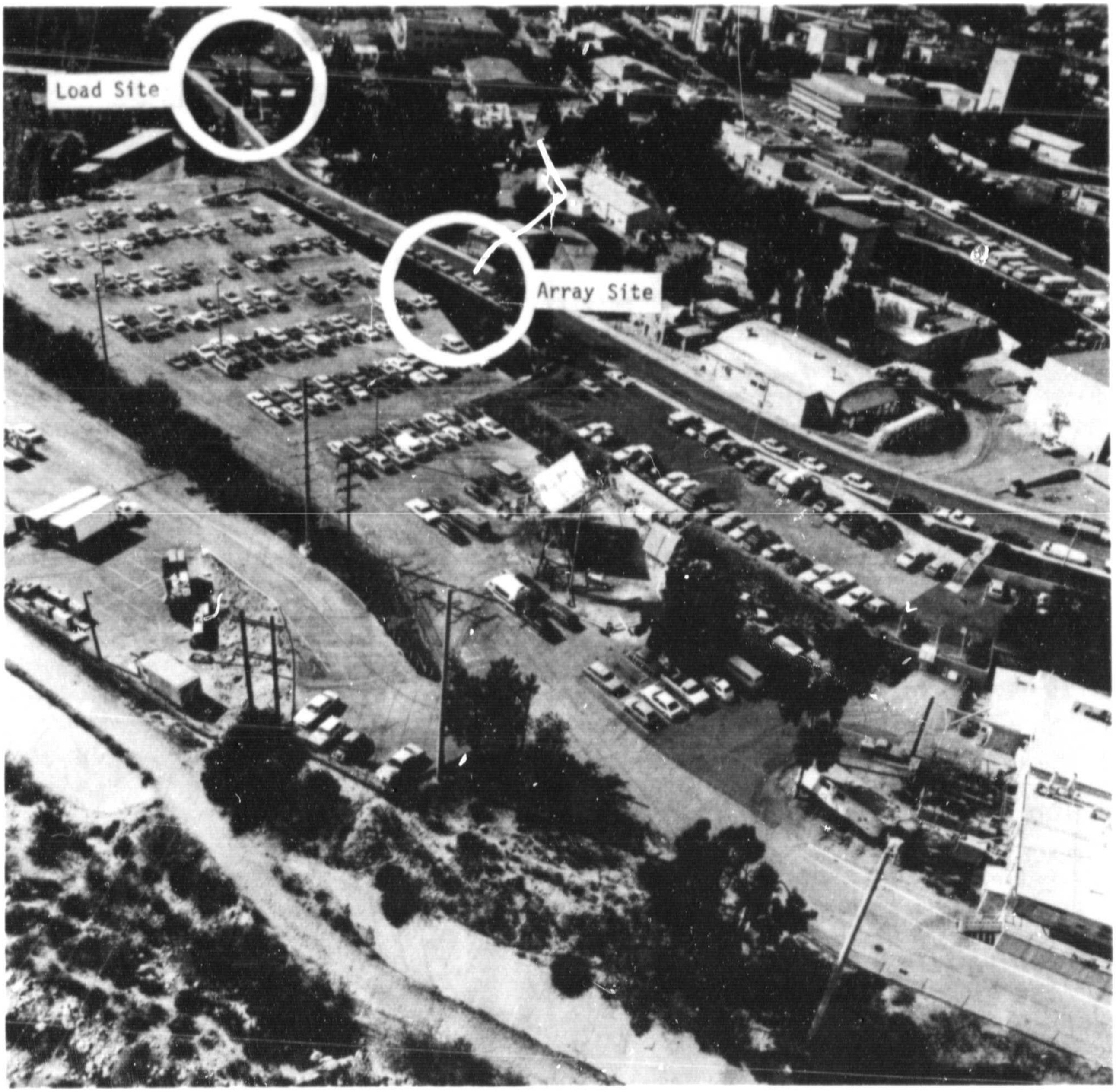

Figure 5. JPL Electric Load and Solar Array Sites

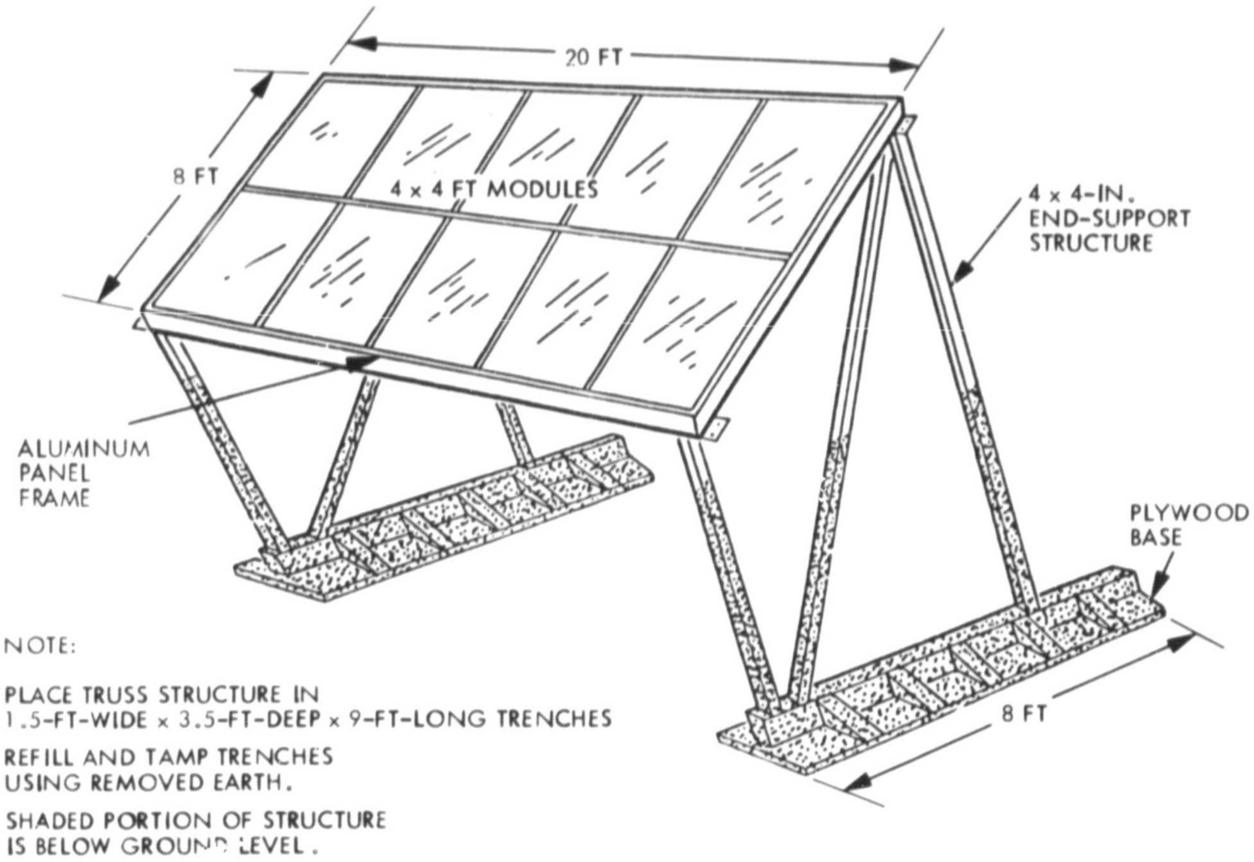

Figure 6. Solar Array Structure (6)

the excavated soil is replaced on the truss base and tamped. The structure is said to be capable of supporting array loads in excess of 0.0293 kg/cm^2 (60 lbs/ft^2) with a variety of soil covers. Typical array load requirements are 0.01 to 0.015 kg/cm^2 (20 to 30 lbs/ft^2). Wood members are treated to resist rot and termites.

3.5 Power Conditioning Equipment

Many types of DC/AC inverters are available, each trading off advantageous operational characteristics of one kind for some compromise in cost, weight, reliability, design complexity, etc. Newer designs key upon efficiency, low weight, high reliability, rejection of electromagnetic interference, and safety considerations as well as frequency stability, low harmonic content of the output, good voltage regulation and transient response. Transistor-based technology is adaptable to low power applications such as this study, while SCR-based systems are better suited for high power applications that range up to 1 MW. Power transistor heat dissipation characteristics limit their use to applications up to 15 kVA. Variable voltage and frequency adjustments are easily incorporated into transistorized designs. Until recently, transistorized power inverters were inefficient (30 to 40%), possessed high weight-to-power ratios and were relatively expensive.

Large-scale integrated circuits, including the programmable read only memory stored in the AC power source made practical new designs of digital inverters to convert DC to AC. These units have high power-to-weight ratios, have high efficiency (90%) over the no-load to full-load operating range, and are relatively low in cost. Digital synthesis is used to generate a sinewave from a pulse pattern for its 360° period, positive and negative, that is stored on a memory integrated circuit. The digitally synthesized sinewave, Figure 7, has a pattern selected to eliminate low-order harmonics, less than the eleventh, that would otherwise have to be removed with bulky and costly filters. The eleventh and higher harmonics are more easily removed with a simple LC filter. Voltage regulation with the digital synthesizer is achieved by varying the stored dwell time during which the pulse pattern remains at zero volts as the DC voltage increases. Higher reliability is said to result from this inverter design because of the low parts count and low temperature rise.

It is a noteworthy assessment [4] that the high power transistors used in PCE circuitry are still in the research phase of development, and in early stages of development for photovoltaic applications, are inverter designs, the PCE control and protection circuitry. Moreover, powerline noise affects inverter operation.

JPL Facilities Engineering requires the following for a photovoltaic-utility co-generation station:

1. Output voltage regulation within ± 8% of nominal voltage over a full load range at 0.8 power factor.
2. Output frequency regulation within ± 5% of 60 Hz.
3. Harmonic distortion up to 5% maximum

Inverters of a number of manufacturers were investigated. The Sunverter that was developed for photovoltaic applications by Abacus Controls Incorporated, Sommerville, N.J., offered attractive operating protective and safety features that led to its tentative selection for this installation.

The unit selected is rated at 10 kVA, is single phase and phaselocks to the utility grid voltage waveform. At overload or short circuit conditions, a current limit signal overrides the voltage feedback signal and the unit automatically switches operation from a voltage regulated mode to a current

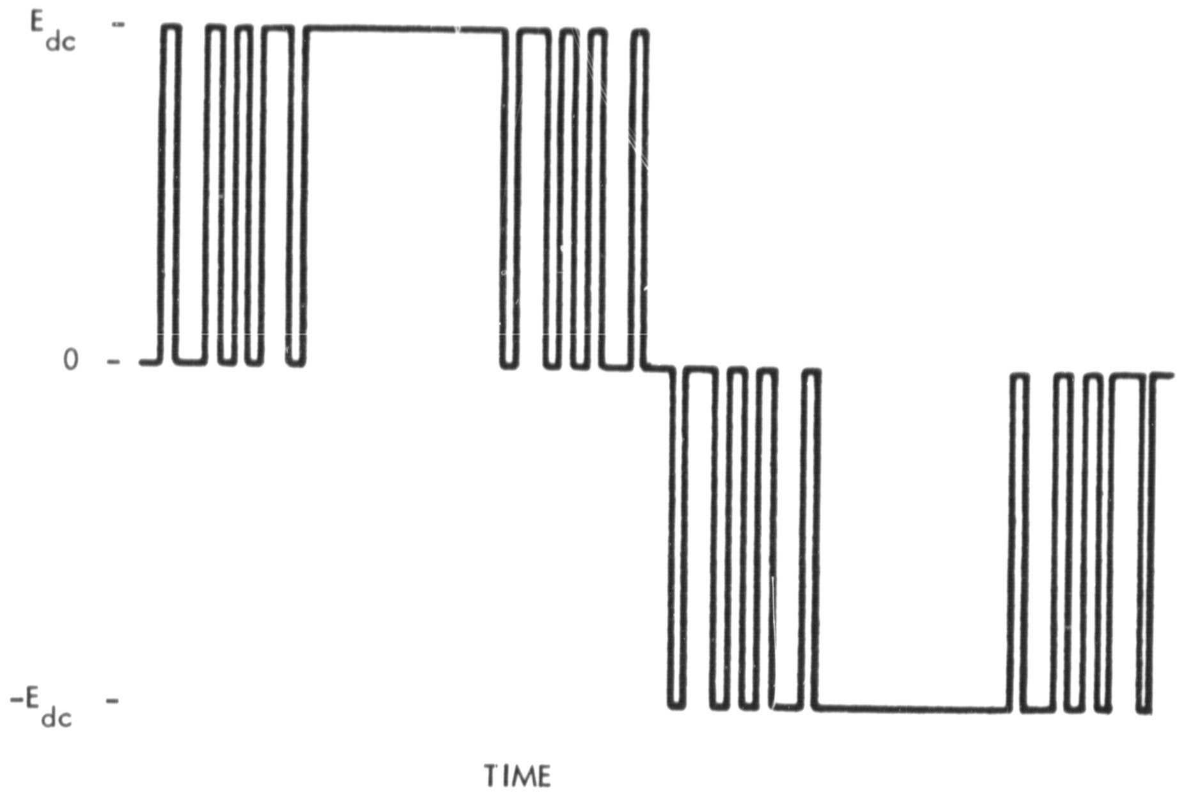

Figure 7. Digitally Synthesized Sine Waves (4)

limited mode. The system automatically returns to the voltage-regulated mode when the overload or short circuit is removed. The unit is said to withstand a short circuit indefinitely. No tuning filters are used in the switching circuitry incorporated in the power stage which permits operation into zero lead or zero lag power factor loads without damage to, or impairment of, the performance of the AC power source.

Solar array voltage input for proper inverter operation must range between 160 to 275 VDC, with automatic start up when insolation conditions enable the array to output above 180 VDC. Automatic inverter shut down occurs when the array voltage declines below 160 VDC or rises above 275 VDC, since the inverter cannot output regulated voltage at 240 VAC with input voltage beyond this range. Output voltage of the array can exceed 275 volts operating cold on a clear winter day with high solar intensity, when a cloud shadow drives the array temperature down and the passing cloud suddenly exposes the cold array to the bright sun. Under these conditions, the solar array effectively open-circuits when the inverter is off, and the inverter later automatically restarts synchronizing into the utility waveform, when the array voltage declines within proper operating range as the array warms. Estimated array output current and power are shown in Figure 8 at the turn-on and turn-off inverter input voltage levels. The magnitudes shown at the noted conditions are at the PCE input from the array.

The output voltage is nominally 240 VAC ± 2%, at 60 Hz ± 0.25 Hz if stand alone, but when utility connected, the waveforms of inverter output current and output voltage are phaselocked to the grid voltage waveform. Maximum harmonic specification of the inverter output current into the utility is 5% total harmonic distortion; ripple current returned to the utility is specified

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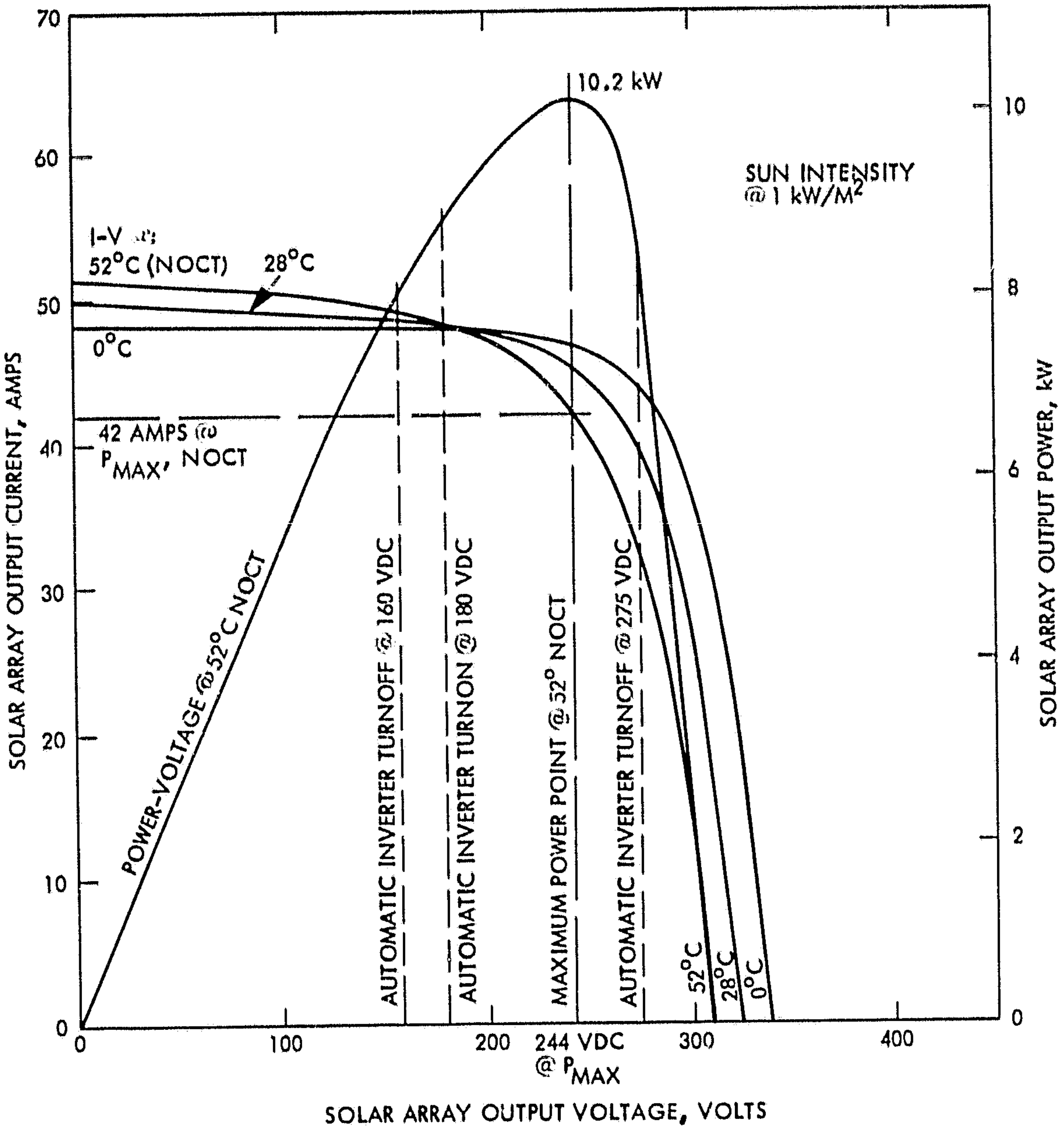

Figure 8. Estimated Array Peak Performance Characteristics for JPL Utility Connected 10 kVA Photovoltaic System as the Power Conditioning Electronics Views the Solar Array.

at 2% rms of DC. The unit also incorporates the following safety features:

- Both lines of the input and output are fused.
- The inverter automatically turns off for power transistor over-temperature
- Inverter automatically disconnects from the utility if
  - utility voltage is less than 216 VAC
  - utility voltage is greater than 264 VAC
  - if current exceeds rating
  - if phaselock is lost
  - if utility power is down

The unit is 24 inches wide by 30 inches deep by 60 inches high.

3.5.1 Maximum Power Point Tracker

An optional solar array maximum power point tracker (MPT) is available, that continually senses the maximum power voltage point of the array characteristics that changes with insolation and temperature in the seasonal manner illustrated in Figure 9, and in fact can undergo similar changes within a given day. The MPT forces the solar array to operate at the maximum power current and voltage coordinates of its output characteristics to transfer the greatest possible array energy to the PCE for the given set of conditions.

A study (3) suggests decreased advantages of an MPT option with some inverter designs. An inverter feature of value if an MPT is considered is the range of array input voltage to the inverter for the unit to sustain its specified regulated output voltage output. A wide range diminishes the need for an MPT. The input voltage requirement for the Sunverter is 160 VDC to 275 VDC which can be expressed as 218 ± 26% VDC, where 0.26 is α, the allowable inverter range fraction.

Array power loss is zero with an MPT forcing operation at its maximum power point, however the tare power requirement of the PCE increases because of the

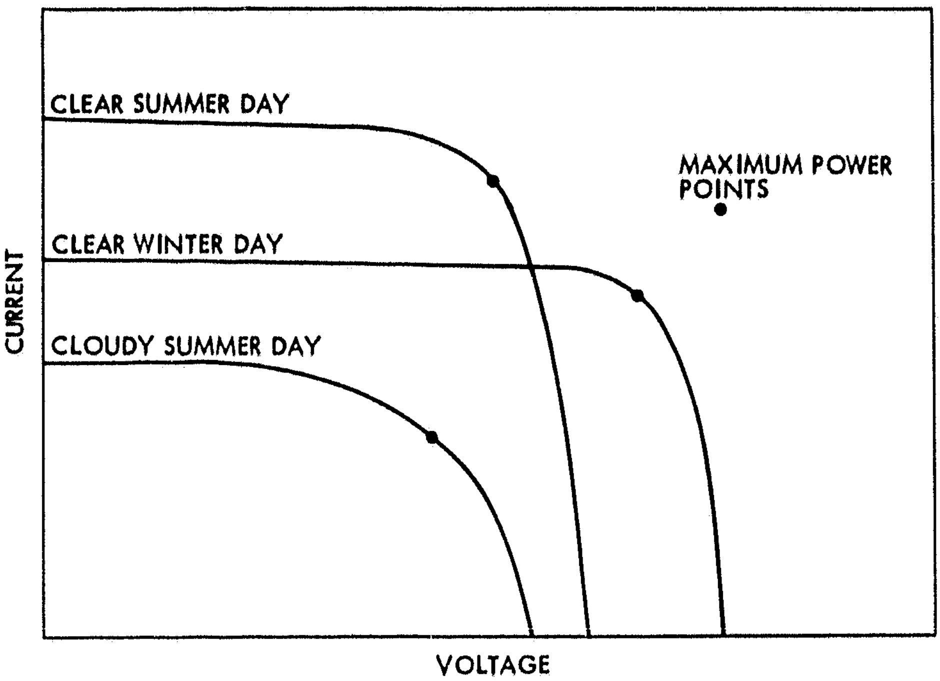

Figure 9. Variations of Solar Array Maximum Power Points

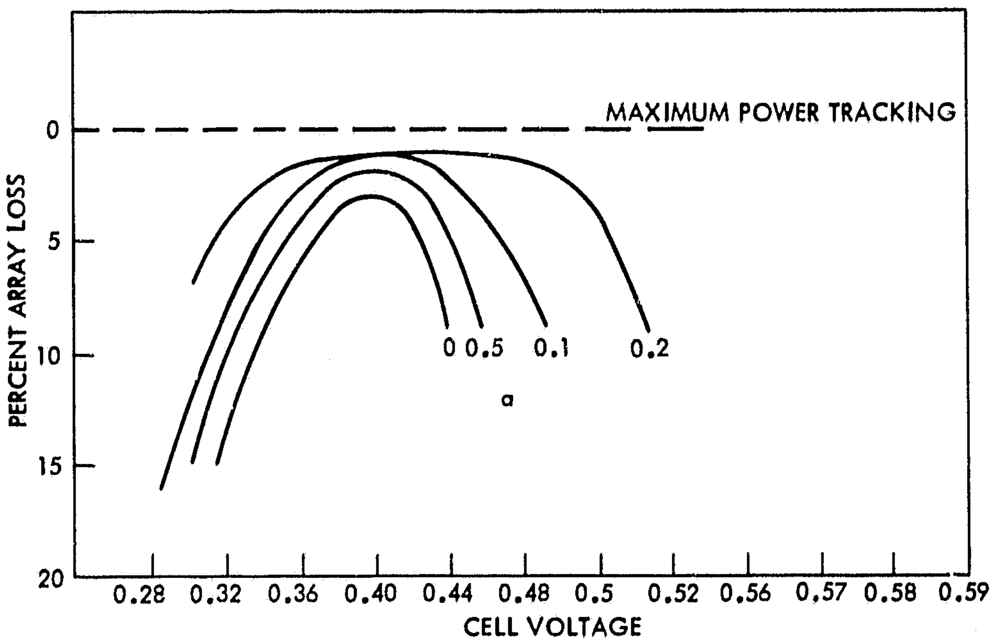

Figure 10. PCE Input Voltage Limit Variations and Off Maximum Power Point Operation Loss (3)

MPT function. As seen in Figure 10, the array loss amounts to about 4% for $\alpha = 0$, a case where no inverter input voltage latitude exists and the array operates off its maximum power point at the inverter input limit. The greater the operation away from the maximum power point, the greater the array energy transfer loss. With $\alpha = 0$, the plot shows the array losses to be sensitive to the design selection of the proper array operating point, and an MPT could be cost-effective.

As the allowable range fraction increases, array losses due to off maximum power operation decrease, and the design selection of the array operating point becomes less critical. Array losses operating with the Sunverter is seen to be less than 2% over a wide range. The loss is low enough to weigh the potential benefit of an MPT against the decrease in system reliability because of the added parts count, the power required to operate the circuit, the affect upon the PCE stability with the added control loop, and its added cost. The maximum power point tracker option is not selected for this application.

4.0 System Performance

The total array area of this system is sized to conditions of 52°C nominal operating cell temperature (NOCT) with insolation at 1 kW/m^2 and at which the array is expected to output 10.2 peak kW, including expected losses. The question now is the performance that can be expected of the JPL PV system during an average year.

A study has been conducted to collate solar/weather data at sites about the U.S. to estimate solar array performance for future installations. (7) Unfortunately, Los Angeles at 34° N latitude is not among those chosen for investigation, but nearby El Toro at 33.67 N latitude is included in the survey, and data for that site will be used in this analysis. The result will be optimistic since Los Angeles lacks the atmospheric clarity of El Toro. The result will also be optimistic because the data assumes array operation at the maximum power of its performance characteristics. Since no maximum power tracker is included in this installation, the data presented are optimistic by about 2% (Figure 10).

The average daily AC power output from the converter per unit area of the array, QE/A, in kWh/m^2, is given by

$$QE/A = \eta_{pc} \times \eta \times QS/A \qquad (1)$$

where:

η_{pc} = efficiency of the power conditioning equipment; specified at 90% in this application

η = the average array conversion efficiency for a given month

QS/A = average daily insolation per unit array area for a given month, in kW/m^2

A procedure is outlined [7] to solve equation (1) for the estimated AC power to the loads using average parameters that are site dependent for the given month. In Table 2, a factor is shown describing the expected average clearness for the month at the site. Also shown, is the average optimum array tilt angle for the month, were the array tilt angle adjustable. TM is the average ambient temperature for the month considering the average wind speed for the site (2 to 3 m/sec). At the fixed tilt of 34°, the average incident sun angle on the array becomes |34°-SM|. The average solar cell temperature, T_c, can then be obtained, which leads to the module efficiency, η, calculated by

$$\eta = \eta_r \, [1-\beta\,(T_c-T_r)]$$

where

η_r = module reference efficiency

$$= \frac{\text{module Pmax}}{\text{mod. area} \times \text{reference insolation}}$$

$$= \frac{Pmax}{A \times (\frac{QS/A}{A})i}$$

β = array efficiency temperature coefficient

$$= \frac{1-(n_2/n_1)}{T_2 - T_1}$$

where: module efficiencies are n_1 and n_2 at temperatures T_1 and T_2 at the same insolation conditions.

T_r = Reference temperature (NOCT = 52°C)

The average daily insolation per unit array area for a given month, QS/A, is taken from a tabulation of average monthly kW/m^2 insolation data at the site (7) interpolated to a 34° fixed array tilt angle. The inverter AC power output in kWh/m^2, QE/A, can now be calculated and is listed in the last column of Table 2.

A 10 kW peak array output requires utility power supplement to support the load profile at the JPL stations that peaks at 19.4 kW, but it is of interest to estimate the portion of the electrical load supplied by the 10 kW photovoltaic system, and also to estimate surplus power returned to the net if the array were to be scaled up to 30 kW (requiring three 10 kVA capacity inverters in parallel).

QE/L is the potential solar fraction that represents that portion of the load that can be supported by an array that is backed by infinite lossless storage; i.e., all converted array energy is utilized. QE is the AC power output of the converter and L represents the average daily electrical load (kWh) in a given month, a constant at 347.4 kWh for the JPL Stations. Table 3 lists QE/L values for differently scaled systems that are calculated from the monthly QE/A values shown in Table 2 with the 115.3 m^2, 10 kW array, and with arrays scaled to 20 kW (42 parallel modules) and 30 kW (63

	ATMOSPHERIC CLARITY FACTOR	OPTIMUM ARRAY TILT	TM °C	AVERAGE CELL TEMP., °C	MODULE EFFICIENCY, %	QS/A kWh/M^2	QE/A kWh/M^2
JAN	0.578	63°	12	37	9.4	4.52	0.382
FEB	0.603	52°	13	39	9.3	5.29	0.443
MAR	0.621	37°	13	41	9.2	5.99	0.496
APR	0.617	24°	12	39	9.3	6.18	0.517
MAY	0.598	12°	16	36	9.4	5.97	0.507
JUN	0.608	9°	18	41	9.2	6.02	0.499
JUL	0.665	10°	21	44	9.1	6.60	0.539
AUG	0.656	24°	21	45	9.0	6.59	0.535
SEP	0.617	32°	20	44	9.1	6.06	0.494
OCT	0.601	44°	18	42	9.2	5.48	0.452
NOV	0.586	57°	15	38	9.3	4.73	0.398
DEC	0.571	64°	13	34	9.5	4.32	0.370

Table 2. Average Daily System Operating Parameters During the Year.

parallel modules). The series length of 15 modules remains the same in the larger arrays.

At this stage of the analysis, the dimensionless QE/L factor contains elements responsive to the array area, its efficiency and its tilt angle, and, given the type of system load profile, the probable system power surplus can now be evaluated. No power surplus above load requirements had been expected from the 10 kW array, and negligible surplus can be expected from the 20 kW array, just on transient occasions in winter if operated cold at elevated solar insolation. In confirmation, the QE/L values for the 10 and 20 kW array system are shown too small to generate a surplus since their QE/L - F values are negative. The solar fraction, F, is the portion of the electrical load that is supplied by the photovoltaic system. In the pursuit of determining surplus power, the 10 kVA and 20 kVA systems are now disqualified, and just the solar fractions for the system with the 30 kW array are tabulated in Table 3, averaged for each calendar month.

The daily average of surplus energy for a given month that is converted by the array and the consequent surplus power returned to the utility net by the inverter is given by:

$$SP = (QE/L - F)L, \text{ kWh/day},$$

and estimated daily values per month are shown in Table 3.

The monthly power requirements of the load (L x days) are also listed and totaled, and those portions of the monthly loads supported by photovoltaics each month (F x L x days) are shown and totaled. Annually, about 15% of the loads are supported by the 10 kW array, and 42% by the 30 kW array that also returns 6505 kWh to the power utility.

ARRAY SIZE, kW →	QE/L			SOLAR FRACTION,	AVERAGE DAILY SURPLUS POWER RETURNED, kWh/DAY	MONTHLY LOAD, kWh	MONTHLY PORTION OF LOAD SUPPORTED BY PV SYSTEM, kWh	
	10	20	30	30	30		10	30
JAN	0.127	0.253	0.380	0.31	24.3	10,769	1,365	3,338
FEB	0.147	0.294	0.441	0.35	31.6	9,727	1,430	3,405
MAR	0.165	0.329	0.494	0.38	39.6	10,769	1,773	4,092
APR	0.172	0.343	0.515	0.44	26.1	10,422	1,788	4,586
MAY	0.168	0.337	0.505	0.44	22.6	10,769	1,812	4,739
JUN	0.166	0.331	0.497	0.49	2.4	10,422	1,726	5,107
JUL	0.179	0.358	0.537	0.53	2.4	10,769	1,927	5,708
AUG	0.178	0.355	0.533	0.52	4.5	10,769	1,912	5,600
SEP	0.164	0.328	0.492	0.46	11.1	10,422	1,708	4,794
OCT	0.150	0.300	0.450	0.41	13.9	10,769	1,616	4,415
NOV	0.132	0.264	0.396	0.36	16.0	10,422	1,377	3,648
DEC	0.123	0.246	0.368	0.31	20.1	10,769	1,322	3,338
				Annual Total	6502	126,800	19,756 15%	52,770 42%

Table 3. JPL Load Support and Surplus Power Returned with System Scale-up.

5.0 Utility Grid Interface

The PV system in this study is designed to operate in parallel with the local utility that specifies the interface, in this case the Southern California Edison Company (SCE).(8) Some SCE guidelines are:

Manual Disconnect

Since the JPL PV installation will generate less than 200 kVA, SCE will waive a manual disconnect switch at the meter and will use instead the meter itself as the power disconnecting device; see Figure 11. The upper of the two meters shown in the Figure would be installed to measure surplus power returned to the net with a larger system.

Automatic Disconnect

The JPL photovoltaic system PCE is to be equipped with an Edison line voltage relay, or contactor, to prevent the solar array from being connected to a de-energized power grid. The relay is mechanized to automatically disconnect the PV system when the grid is inoperative and to prevent its reconnection until the utility power service is restored. This relay is noted as the generator contactor in Figure 11 and master contactor in Figure 12. Since the inverter used in this study is line-commutated, it operates as a redundant disconnect device in the event of power disruption since the lack of a voltage waveform on the grid automatically turns off the inverter.

Dedicated Transformer

The JPL PV system is to have utility service through a dedicated distribution transformer that serves no other customer. The dedicated transformer ensures that the system is not isolated in a manner to cause its array to support the loads of other customers. It also aids to confine waveform abnormalities produced by a PV system to the customer's own service.

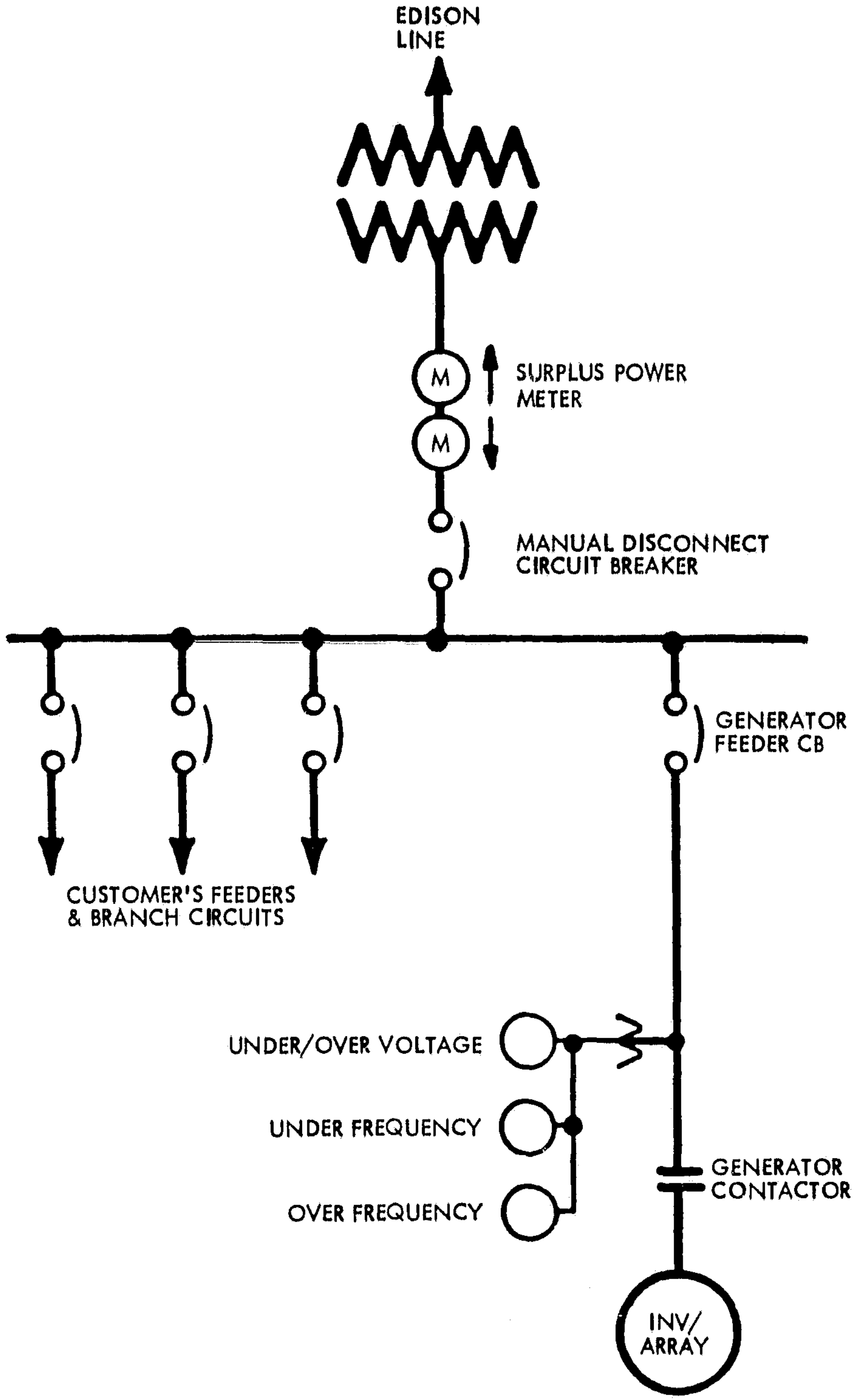

Figure 11. The Grid Interface (8)

VARs

All reactive power requirements for induction generators or power inverters shall be supplied by SCE in order to reduce the possibility of self-excited operation at a co-generator installation. VAR supply from the utility will be made available at no charge to the customer, except in unusual situations.

Harmonics

This stipulation is more of an alert than a requirement since at present no standard exists for the harmonic output of power inverters. If a customer using an inverter with an output having a high harmonic content is found to be interfering with other customers, or if standards are adopted in the future, the customer with a PV generator may be required to install filtering to bring the harmonic output of this inverter to an acceptable level.

Meters

Existing meters at all generating installations will be equipped with a detent to prevent reverse registration. For anticipated generation of surplus power, SCE will install a separate meter to record power delivered to the net as shown in Figure 11.

6.0 Instrumentation and Data Acquisition

An AC watthour meter will be used to record the power input to the special bus supporting the loads of the JPL stations, Figure 13. Two input power sources serve the grid interface to the special load bus, the power conversion equipment and the utility, and each of these sources will be monitored by an AC watthour meter for their power contribution to the interface. A DC watthour meter monitors the output of the array.

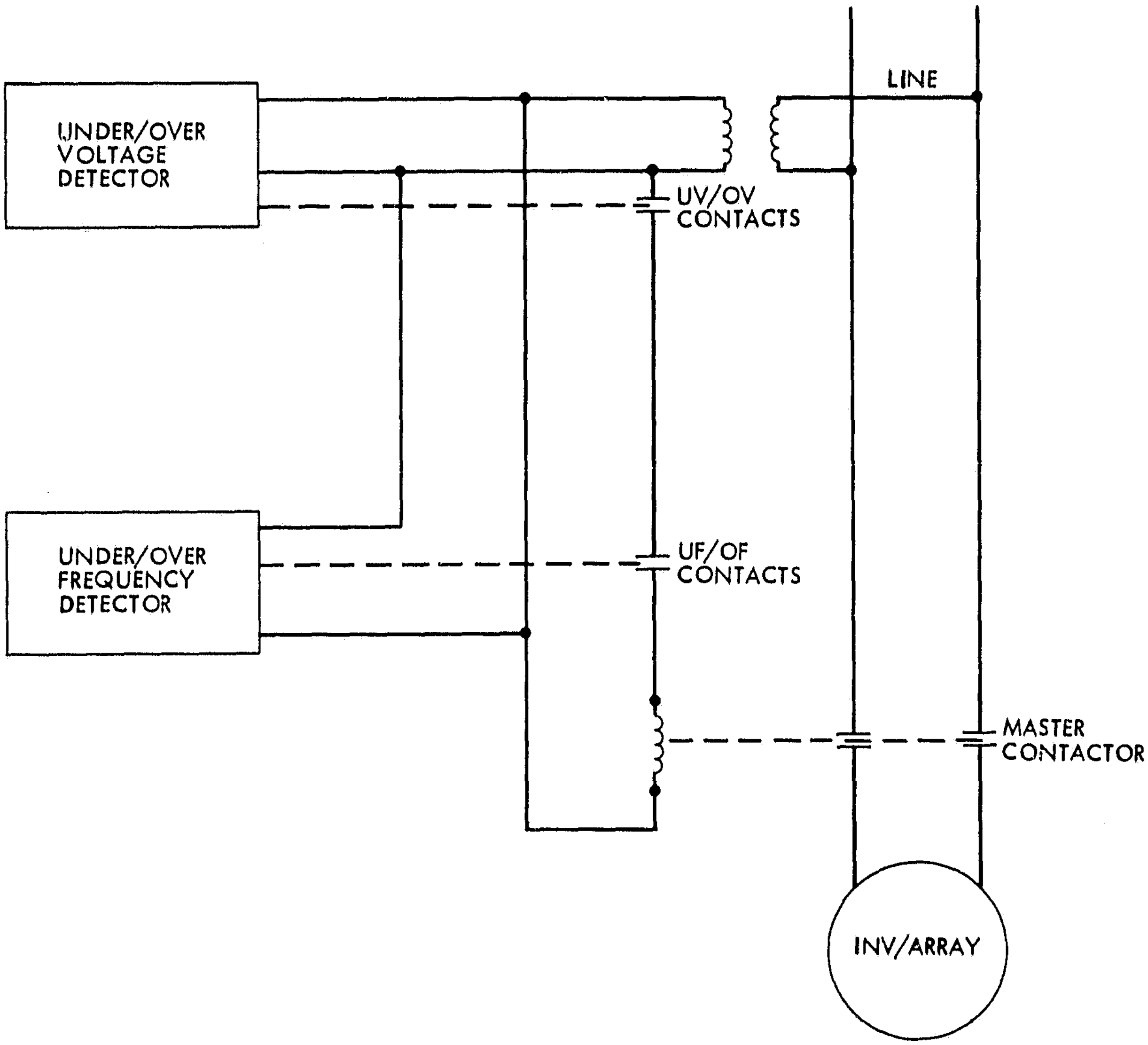

Figure 12. Single Phase Relay/Contactor at the Grid Interface. (8)

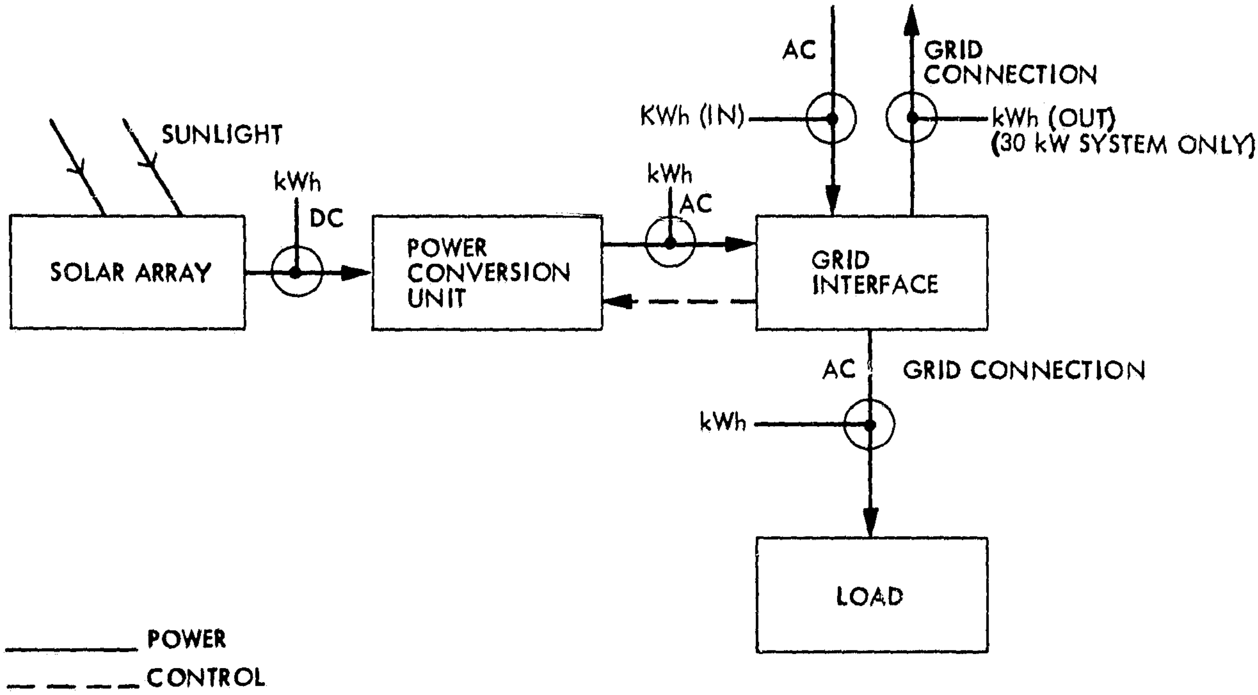

Figure 13. The Photovoltaic Power System Instrumentation.

Data from these instruments will be recorded weekly. The inverter, the grid interface electronics and the associated instrumentation will be housed in a prefabricated grounded metal structure. Instrumentation for monitoring the loads will be located in one of the station buildings where the inverter and DC watthour meter are located.

Visual module inspection is required upon their receipt, and periodically during the study. Array performance evaluation is best made with periodic I-V characteristics recorded of each module, but such measurements are labor intensive and time-consuming, and it is expensive to organize the module circuit and instrumentation to automate these measurements with minimal manpower costs. Current measurements for each series string of modules are useful, although they provide ambiguous indications of a single module failure. A precision Hall effect DC measurement instrument with a clamp-on probe can quickly measure the current in each series string of modules and measurements taken four times a year under clear sky conditions could be used to track module performance. Inconsistent current magnitudes indicate probable module problems and investigative module measurements can be restricted to the faulty series string.

A calibrated secondary standard cell made of a cell used in the modules will be useful to determine insolation. Array temperature evaluation is perhaps easiest with one module in the array fitted with a number of thermocouples, front and back, to determine the temperature gradient and to ascertain a location on the module where a single thermocouple could best read an "average". Assumptions will have to be made that this location reads the average temperature of each module and that this is the average cell temperature as well. Measurements of module series string currents, insolation and module temperature will be made quarterly, and the data will be reduced to determine array performance changes with time.

7.0 Cost and Schedule

The DOE Low Cost Solar Array Program of recent years emphasized module reliability and efficiency as well as low cost. Exhaustive investigations of module problems and failures in the program have alerted manufacturers to proper production practices and material selection, and discouraged cutting corners. No manufacturer desires documented post mortems of their product describing failure due to negligent workmanship, improper choice of materials, faulty design, or unsuitable production procedure. Solar module quality has become competitive, and with solar modules as other products in the marketplace, higher price and higher quality do not always equate. Accordingly, modules have been selected for the JPL system that lie within the lowest dollar per watt cost band of Figure 14, an organization of the range of module costs for the time.

Cost savings are realized with volume module purchases; about $54K can be saved should a 30 kVA system be installed at the start. It is assumed however, that the program will be undertaken in two phases. The first, at 10 kVA peak capacity, pioneers the installation and the interfaces, debugs, and establishes the routine tests and reports. Expansion to a 30 kVA adds new operational complexity with surplus power being purchased by the utility and with the utility interface having to be re-established. Only costs for the major equipment used in the scale-up are included for the second phase, with the ancillaries (monitoring equipment, cable, switches, etc.) assumed to have been selected with consideration for a larger system at the later time, Table 4. The second column in the table are the costs to enlarge an existing 10 kVA system to 30 kVA. The total of both columns are the costs to establish a 30 kVA system at the start, less $54K for larger volume purchase of modules. The direct costs are same regardless of the system size. A program implementation plan is shown in Figure 15.

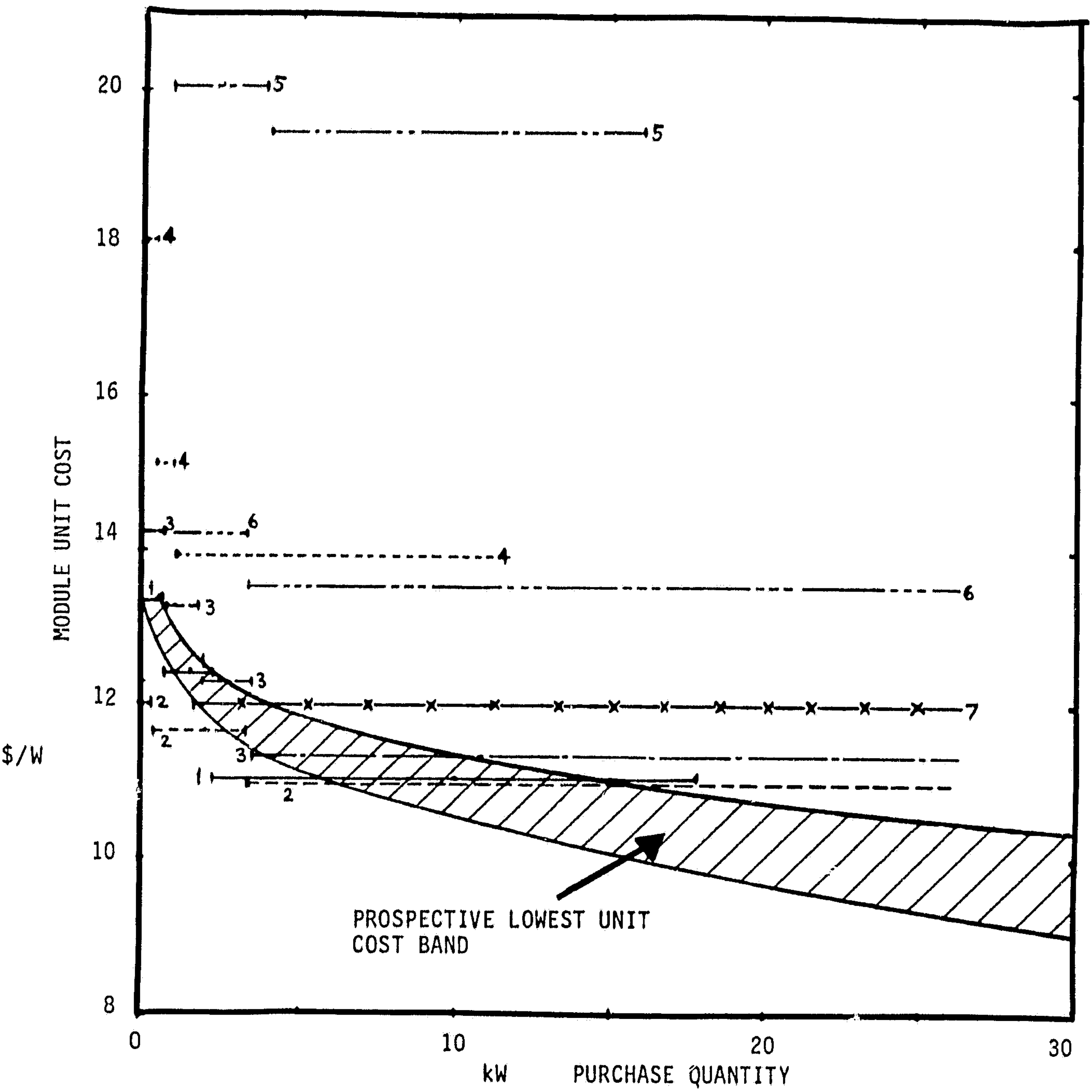

Figure 14. Unit Cost Band for Silicon Modules as of April 1981, Numbers Refer to Modules of Various Types. Source: L. D. Runkle at JPL.

Direct Costs	
Labor (Engr: 1.5 MY, Tech: 1 MY, over 3 years)	105
Travel	2
Technical Support	15
Publications	5
Equipment Rental	12
	139

	Phased Installation		One Installation
System Capacity	10 kVA	30 kVA	30 kVA
Procurement			
Solar Modules	110	200	
Module Mounting Structure	11	20	
PCE	16	32	
Instruments	15		
Maintenance	10		
Power Cable, Installed	5		
Switching Electronics	3		
Fence	2		
Signs	1		
Misc.	4		
Total	177	252	
Total with Direct Cost	316		
Indirect Costs	102	41	
	418	293	657

Table 4. System Costs, $K

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Procurement                      -------<>          -------<>*
Installation                         ---<>             ----<>*
     Array                       -------<>          -------<>*
     PCE                         -----<>            -------<>*
     DC Power Cable & Power Bus   --<>
     Utility Interface           -----<>
     Instrumentation             -------<>
Checkout & Debug                          --<>
Data Acquisition                             ---------------------------<>
Maintenance                                  ---------------------------<>
Reports: Monthly, Quarterly
    and Annual                      ---------------------------------------<>
Final Report                                                               <>

* System Capacity Increased to 30 kVA
```

Figure 15. JPL PV System Implementation Plan

8.0 Conclusion

The solar array of the JPL Photovoltaic (PV) system will contain 315 solar modules mounted on a ground based wooden structure with fixed orientation. The peak output of the conditioning electronics is about 10 kVA supplying power at 240 VAC to selected loads, with no surplus power or storage, and with the utility supplying power to that portion of the loads unsupported by the array. If expanded to 30 kVA peak capacity, system analyses indicate increased photovoltaic support of the loads from 15% to 42% and surplus power returned to the utility grid.

Power Conditioning Equipment (PCE) protective devices are inadequately developed, and the PCE can adversely react to line noise. The high power transistors and the new digital circuitry employed in the equipment are in an early stage of development. The system will be instrumented to develop a model station to optimize procedures and to explore design refinements that best match the photovoltaic system performance to utility requirements. Arrangements to have small generating systems cohabit the electrical power distribution network with the utility are still rudimentary.

A positive aspect of a review of the electrical utility accommodations for PV system interconnection to the power grid is that the utility substation current surge protection devices appear adequate, considering the intrinsic high impedance in PV systems. The status of the balance of the utility-PV system technical interface is disappointing because of inadequate research and the consequent inadequately developed guidelines. Little is established to avoid system unbalance; power factor or reactive power have no standard definition with respect to the non-sinusoidal operation of modern inverters; while it still may be economical to employ line capacitance at the terminals of PV installation to correct badly lagging power factors, the resonance created may be of greater concern; PV systems will have to eliminate network interfering harmonics it produces or cease operation, but the local utility issued no harmonic specifications, and existing line harmonics have rarely been measured; no guidelines exist for PV system grounding or for the use of isolation transformers; present meters cannot meaningfully measure in the non-sinusoidal and harmonic ladened circuit environment created by PV system operation.

Guidelines once set for individual PV systems may have to be restructured after a utility is heavily populated with dispersed co-generators, since little is known about the cumulative effect of many co-generators and the manner the abnormal operation of one may affect the operation of others; and little is known of the cumulative effect upon the net of a multiplicity of PV generators reacting to transient solar conditions.

REFERENCES

1. "Federal Photovoltaic Utilization Program Plan", JPL internal document 5260-1, Oct. 1979.

2. "Distributed Photovoltaic Systems: Utility Interface Issues and Their Present Status", M. Hassan and J. Klein, JPL Publication 81-89, September 1981.

3. "A Solar Photovoltaic Flat Panel Applications Experiment at the Oklahoma Center for Science and Arts", DOE Contract DE-AC04-78-E123063, Science Applications, Inc., June 1980.

4. Photovoltaic Power Conditioning Development, R. Powell, et al, JPL internal document 5210-18, prepared for DOE, January 1982.

5. "Investigation of a Family of Power Conditions Integrated Into the Utility Grid", DOE Contract DE-AC02-79ET 293359, Westinghouse Corp., Draft Final Report, January 1981.

6. Wilson, A. H., "Low-Cost Solar Array Structure Development", DOE/JPL-1012-53, June 1981.

7. Evans, D.L., Facinelli, W.A., and Koehler, L.P., "Simplified Design Guide for Estimating Photovoltaic Flat Array and System Performance", SAND 80-7185, March 1981.

8. Southern California Edison Company, "Guidelines for Operating, Metering, and Protective Relaying for Co-Generators and Small Power Producers", June 1981.