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A PRELIMINARY ANALYSIS OF THE IMPACT ON UTILITY DISTRIBUTION SYSTEMS OF POWER FEEDBACK FROM RESIDENTIAL PHOTOVOLTAIC SYSTEMS

FOR THE UNITED STATES DEPARTMENT OF ENERGY
DIVISION OF DISTRIBUTED SOLAR TECHNOLOGY

THE AEROSPACE CORPORATION

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A PRELIMINARY ANALYSIS OF THE IMPACT ON UTILITY
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RESIDENTIAL PHOTOVOLTAIC SYSTEMS

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FOREWORD

This report documents the results of an analysis of impacts on utility distribution system from residential photovoltaic generation systems which feedback power to the utility system. The study was conducted under Contract No. EY-76-C-03-1101, Project Agreement 8, Modification 5 "Photovoltaic Mission Analysis" for the US Department of Energy, Division of Distributed Solar Technology. The analyses described here were carried out as part of Task 2: Intermediate-to-Large Load Center Applications for Photovoltaic Electricity.

This document was prepared by Mr. W. Kammer of the Energy Systems Directorate. The work on the program was accomplished by members of the Energy Systems Directorate of the Energy and Resources Division of The Aerospace Corporation. Mr. Paul Maycock, Acting Chief of the Photovoltaics Branch was the DOE Program Manager for this contract, and Dr. M. B. Watson, Principal Director of the Energy Systems Directorate, was the Principal Investigator. Dr. S. L. Leonard, Director, Photovoltaic Projects office, provided the day-to-day program management.

The author wishes to express his appreciation for the contributions to this investigation made by Dr. F. C. Finlayson of the Aerospace Corporation and also acknowledge the help of Ms. P. W. Dunn in typing the text.

Section I

INTRODUCTION AND SUMMARY

Several recent studies (e.g., Refs. 1, 2) have indicated that the use of roof-mounted photovoltaic generators to serve the electric power demand of single-family residences is perhaps the most promising large-scale terrestrial application for this solar energy conversion technology. The preferred configuration appears to be one in which the photovoltaic system (including electric storage capacity, if any) is so designed that a significant fraction, but not all, of the required energy is of solar origin, with the remainder provided by the conventional utility grid.

The existence of the connection to the grid, i.e. to utility power distribution systems, introduces the possibility of feeding back excess photovoltaic electricity (generated, for example, when the residence demand is low during a period of high insolation) into the grid for use by other customers. The economic attractiveness of the residential photovoltaic application would be considerably enhanced if such feedback took place and the owner of the photovoltaic system received some form of remuneration for the energy provided. The question of how to pay the photovoltaic system owner for this energy, and how much, is a complicated one that has not been studied in detail. It is, however, clear that before this question can be answered it will be necessary to determine how much it would cost the utility to accept the feedback power, i.e. to identify the changes that would have to be made in utility equipment or procedures and to compute the economic impact of those changes. It is to this latter issue that the study reported in this document is addressed.

1.1 Study Objective and Scope

The objective of this study has been to make a preliminary but quantitative assessment of the technical and cost impacts on utility distribution systems resulting from the feedback of power into the grid from on-site residential photovoltaic systems. It was assumed that the

photovoltaic systems were intended, and designed, primarily to serve the electric loads of the homes on which they were located. It was further assumed that any power generated in excess of these requirements would be fed back into the utility distribution grid to serve other loads.

Because of the limitations in available time and resources, it was necessary to restrict the scope of the investigation in several respects. As is indicated above, only residential loads and residential photovoltaic systems were considered. Further, only one distribution system configuration was represented in the analysis, and the assumption was made that all photovoltaic feedback power was expended within the confines of the basic local unit of the utility distribution system (i.e. no power feedback through the distribution substation). For simplicity, the photovoltaic systems were treated as if they were all identical and as if they were mounted on similar single-family homes.

The degree of photovoltaic penetration was not specifically defined but was assumed to be substantially less than 100% for the whole distribution system. Cost figures, however, were computed as if every house served by a given distribution transformer were equipped with a photovoltaic system, and the results were normalized with respect to the length of the associated distribution line (i.e. expressed on a per-mile basis) as though the photovoltaic penetration on that unit length were 100%. It was felt that expressing the results in these terms would facilitate their convenient extension to larger systems or to different degrees of penetration.

Although these restrictions on the scope of the inquiry limit the generality of the conclusions to some extent, it is believed that the results are broadly representative of conditions that would exist with other load categories, other utility system configurations, other photovoltaic designs, and other degrees of penetration.

1.2 Analysis Approach

The initial step in the approach used in this study was to select a particular baseline utility system configuration supplying the electrical demands of homes without photovoltaic generation systems, to define a conceptual design for the baseline distribution system; and to analyze the power handling capacity of the system. This baseline configuration was defined to a level of detail that identified all major components and specified their ratings. The operation of the baseline design was then analyzed in the case where photovoltaic systems were present and feeding back excess power into the grid. The power levels through the various system components under these conditions were determined and their effects analyzed in order to identify whether over-stress or unsafe operating conditions were introduced into the distribution system. The effects of fault conditions during steady state operation were investigated and evaluated in terms of the baseline protection and fault isolation design. All requirements for redesign or changes in configuration were then expressed in terms of the associated increases or decreases in capital cost relative to the baseline system cost.

1.3 Significant Findings

The analysis identified three changes in distribution system design that would be required before residential photovoltaic systems could be safely and reliably operated with power feedback to a utility line: (a) an increase in distribution transformer capacity, (b) improved secondary isolation capability (additional switches) on these transformers, and (c) power factor correction. (The need for power factor correction is a consequence of the use of static inverters to convert the DC electric power from the photovoltaic array to the AC needed to serve the residential loads.) In addition, it was observed that, if any credit is to be assigned to the photovoltaic system owners for the feedback power delivered to the utility, a more sophisticated electrical energy metering system will be required.

It was estimated that the cost of increasing the ratings of the distribution transformers to accommodate the high peaks resulting from feedback photovoltaic power would amount to \$4,200 per mile of distribution line. The cost of adding positive disconnect switches on the secondary sides of these transformers would be of roughly the same order, \$2,300/mile, but the cost of power factor correction would be much larger, approximately \$30,000 per mile. Since the cost per mile of the distribution line in the baseline case is about \$27,000, these three extra items would add to the system costs an amount equal to about 133% of the baseline figure. The total cost of a utility distribution system, however, is heavily dominated by substation costs. Consequently, the cost of the above changes would amount to an increment of only about 15% of this total distribution cost. (Since the computation is carried out on a per-mile basis, these comparisons are based on the tacit assumption that there is 100% photovoltaic penetration of the small sections of the grid that are being considered.)

The additional cost of providing metering capacity with the potential for separately measuring and recording the flow of electricity in both directions between the utility grid and the photovoltaic-equipped residence was estimated as between \$100 and \$400 per installation, depending on the degree of sophistication used in the measurements. This would correspond to incremental system costs, for the residential density of the baseline configuration, of between \$10,500 and \$42,000 per mile. The cost increase from recomplexing metering systems alone, therefore, could be in excess of 15% of the total distribution cost.

Section II

BASELINE DESIGN SYSTEM DESCRIPTION

In this section the development of the configuration for the baseline distribution system is described. Reasons for the selection of the particular baseline distribution system design that was used are included, as

are brief discussions of the various factors considered in making the selection. Because of the restricted scope and time allowed for the conduct of this study, careful attention was given to the level of detail in the definition of the engineering design in order to insure the identification of all major issues without spending time on insignificant details.

2.1 Fundamental Distribution System Concepts

The traditional layout of the transmission and distribution elements of a utility system is illustrated in Figure 2.1. As indicated in this figure power is produced by generators connected to various types of prime movers. It is produced at between 5 to 30 kV in the machine and is then transformed to a higher voltage of between 115 to 765 kV and transmitted to transmission substations near load centers. At transmission substations, the line voltages are typically reduced to a subtransmission voltage of from 34 to 69 kV and then transmitted to distribution substations. In some cases the subtransmission system is omitted and the voltage is reduced directly to distribution circuit levels at the transmission substation. At a distribution substation the high voltage portion of the distribution circuit is typically referred to as the primary whereas the low voltage side, 240/120 V, is called the secondary. The primary distribution voltage varies widely, from 2.4 to 35 kV, the particular value of voltage selected being dependent upon factors such as load density, circuit length, and certain legislated requirements. In any utility, most individual customers are supplied with 120/240 V from distribution circuits through single-phase, step-down distribution transformers. As the customer's load increases, he may elect to have the utility serve him with three phase power at a higher voltage directly from a distribution or subtransmission circuit. If the load is very large, as in steel-making or aluminum-refining plants, service may be at transmission voltage levels. The small load of a single family residence is, however, always supplied at a secondary voltage of 120/240 V, single-phase.

Figure 2.1. Traditional Concept of Utility System Design

The three basic distribution concepts most frequently used by utilities are the radial, loop, and network configurations. Diagrams of these concepts are presented in Figure 2.2. Of the three, the radial concept represents the simplest form of circuit. Its principal element is a feeder line that originates at the distribution substation and extends to a convenient point, called the feedpoint, that is usually near the geographic center of the service area. At the feedpoint the circuit branches into several radial circuits in sufficient number to serve the customers in that area. Loads are connected only to the radial circuits and not to the feeder. The radial concept has provisions for sectionalizing the radial circuits in the event of a permanent fault on a radial segment of the circuit.

The loop concept, shown in Figure 2.2b, differs from the radial design in that the distribution circuits can be fed from two or more feeder lines from the substation, with the circuit physically forming a loop through the service area. The loop is operated with the feeders energized at the substation but with one of the loop circuit switches open. In the event of circuit problems, the loop switches can be closed and other switches opened to isolate the faulted circuit without effecting all of the customers on the circuit. In areas with very long circuits, the line switching is sometimes designed to be automatic.

Connecting all of the secondary circuits together over an entire service area creates a network, as illustrated in Figure 2.2c, to which customers are connected directly. The network concept is sometimes used in areas of very high load density such as metropolitan downtown areas. These areas typically have utilities installed underground and also desire a higher reliability of service continuity than do residential areas. When faulted, network circuits clear by "burning open" the fault until the faulted segment is removed, a process that is accomplished without deenergizing the circuit. Networks are typically designed to operate at standard customer service voltages with 208/120 V, three-phase, star-connected systems being common. The network pattern automatically provides multiple pathways for power feed

Figure 2.2. Distribution Circuit Configurations

to the customers. Since circuit identification, isolation, and repair are generally more time consuming for underground configurations, the feature of deenergizing only the damaged portion of the distribution circuit tends to improve overall customer service reliability.

2.2 Baseline Circuit Description

The radial concept is the simplest of the three basic distribution concepts and its electrical performance is the least difficult to analyze. The radial concept is also very widely used (probably because of its low cost) in utilities throughout the country. It may also be the most appropriate concept to use in areas where the customers each have on-site photovoltaic generation systems that may continue to operate even when the utility power fails. Together these reasons appeared to provide sufficient reason to select the radial concept as the basic distribution circuit configuration for this study.

Load planning data supplied by the Los Angeles Department of Water and Power (LADWP) (Ref. 3) included information on expected residential construction designs and load densities. A portion of the data from this source, as adopted for use in this study, is shown in Table 2.1.

As mentioned in Section I, the restricted scope of this study led to the assumption that power feedback circulating in the utility system would be restricted to the local distribution circuits. In other words, excess power generated on one of the feeders of the distribution substation was assumed to be used to serve loads on other feeders of the same substation, so that power feedback across the substation transformers would not occur. It was also assumed that not all of the homes served by the distribution circuit in question are equipped with photovoltaic systems (i.e. photovoltaic penetration is less than 100%), although 100% photovoltaic penetration could exist on one or more individual feeder lines.

GEOGRAPHIC LOCATION	- SOUTHERN CALIFORNIA
RESIDENTIAL LOT DIMENSIONS	- 50 ft WIDE x 50 ft LONG
CORRESPONDING LOAD DENSITY	- 20,000 kW / mi. ²
NUMBER OF HOUSES PER FEEDER	- 732
NUMBER OF HOUSES PER CIRCUIT MILE	- 105

Table 2.1. Service Area Description

The distribution substation defined for this study is rated at 60,000 kVA, and is designed to supply 10 feeder circuits of equal load, serving an area of about three square miles. Each feeder is rated at about 6000 kVA, so that the diversified peak load per house, for the residential densities indicated in Table 2.1, is therefore about 8.2 kW. The LADWP sizes its distribution transformers for about 8 to 9 kW of diversified individual house load in areas where air conditioning saturation is expected to be heavy (Ref. 4). Their practice is to use, where possible, a 100 kVA distribution transformer for every 12 to 13 customers. Similar practices were also identified for the municipal utility serving the city of Burbank, California. This configuration therefore, was selected as the baseline design. A distribution circuit primary voltage of 12 kV was selected for the baseline design because of its prevalence in southern California and other regions of the country. The delta connection was selected for substation transformers because it has the potential advantage over grounded-star systems of substantially reducing ground fault currents.

The analysis focused on the operation of a single distribution circuit feeder, with radial circuits, with the circuit designed and operating at the diversified peak demand of the load. The diversified peak demand for each house was taken to be 8 kW, on the basis, as discussed above, of LADWP data.

Overhead distribution circuit construction was selected as the baseline construction design. Primary conductors were assumed to be solid number 8 AWG copper, supported by pin type insulators on cross arms mounted on 40 foot class II wood poles. Pole spacing was selected as 150 feet, so that there are 35 poles per mile of line. The baseline system also includes pole-mounted, single-phase distribution transformers connected line to line, with each transformer rated at 100 kVA and nominally serving 12 houses. High-side fuses and arrestors were adopted as standard for each distribution transformer installation. An underground system design was not considered in any detail, but a cursory examination indicated that a design with component capacities such as those specified for the overhead distribution design is

well within the state-of-the-art for below-ground systems. Since the capital cost of underground construction is greater than that of above ground construction by about a factor of 3, however, this alternative was not given further consideration.

The significant parameters associated with the design of the baseline distribution circuit are summarized in Table 2.2.

Section III

PHOTOVOLTAIC SYSTEM DEFINITION

Fairly detailed conceptual designs for photovoltaic systems to serve single-family residences have been developed in several recent studies, most notably those by General Electric Co. (Refs. 5,6), Westinghouse Electric Corp. (Refs. 7,8), and by Spectrolab, Inc. (Ref. 9). It was therefore not necessary (nor possible, within the resources available) to develop a separate system design for the purposes of this study. Instead, the General Electric (GE) design described in Reference 5 was adopted for use in the analysis, largely because the system was more compatible with the power feedback concept under investigation in this study than were those of the other designs mentioned above. Another reason for using the GE design was that the diversified house load of the residence for which the GE system was designed was quite compatible, as will be shown below, with the diversified load assumed in developing the utility distribution system design for this study.

A brief description of the photovoltaic system design is presented in the first part of this section (Section 3.1). This is followed (Section 3.2) by a discussion of the performance of that system in feeding back power into utility distribution circuits.

FEEDER CAPACITY	- 6000 kVA
TOTAL CIRCUIT LENGTH	- 7 mi.
RADIAL CIRCUIT LENGTH	- 1 mi.
DISTRIBUTION TRANSFORMER SIZE	- 100 kVA
PRIMARY CONDUCTOR SIZE, RADIAL	- AWG No.8 COPPER, SOLID
PRIMARY CONDUCTOR RATING	- 90 A
DISTRIBUTION TRANSFORMER DENSITY	- 12 HOUSES PER TRANSFORMER
POLE SIZE AND SPACING	- 40 ft CLASS II, 150 ft SPACING
CIRCUIT CONFIGURATION	- 3 WIRE, NO STATIC WIRE FOR LIGHTNING PROTECTION

Table 2.2. Baseline Distribution Circuit Design

3.1 System Description

The basic photovoltaic system consists of the photovoltaic array, DC to AC inverter, battery storage (if any), and circuit breakers and inter-connecting system wiring. A simplified schematic diagram of the system as conceived for this study is shown in Figure 3.1. The design shown is consistent with the GE design, having a photovoltaic array size capable of driving the DC to AC inverter to the full output of 13 kW. The inverter is of self-commutating design, i.e. the unit generates its own timing signals and hence can generate AC power without being connected to an AC reference signal. (This self-commutating design differs from the design of inverters for large utility DC transmission interties. The converter stations for interties are line-commutated and will not invert the DC power to AC without the presence of an AC reference voltage on the load side of the inverter.)

The GE inverter design uses the utility voltage as a reference for regulating and synchronizing the frequency of the inverter before connecting the inverter to the utility lines. Furthermore, although the inverter operates in the self-commutating mode, the GE design includes a power operated contactor that automatically disconnects the inverter output from the load in the absence of utility voltage. The inverter output is in turn connected to the house main circuit-breaker bus through a circuit-breaker switch. The normal house service utility connection remains unchanged except possibly for alterations in metering to provide separate records of the power flows in the two directions (to and from the utility). The circuit connection shown in Figure 3.1 allows connection of the inverter and, if required, additional metering capability with a minimum of change to the house electric service entrance equipment. The configuration proposed appears to be in compliance with the National Electric Code (NEC).

The inverter power factor characteristics for residential units have not been specifically defined. A review of manufacturer's data on inverter performance disclosed only a limited amount of information on this topic but

ON-SITE CIRCUIT DESIGN

- SINGLE FAMILY R-1 HOUSES WITH 1600 ft² FLOOR AREA
- ALL ELECTRIC HOUSE WITH AIR CONDITIONING, HOT WATER HEATER, CLOTHES DRYER, etc LOADS
- GENERATOR CAPACITY - 13 kW
- TRANSFORMER SIZING - 12 HOUSES/100 kVA TRANSFORMER
- GENERATION EXCESS PER HOUSE - 11 kW

Figure 3.1. On-Site Generator System Configuration Schematic Diagram

generally indicated that inverters present a low-power-factor load to the utility interface. This suggests that the utility will have to supply the reactive power demands of the inverter. Discussions with one inverter manufacturer revealed that his products, of a type and size similar to that specified for the photovoltaic system, have power factors which would range from 0.7 to 0.85, with the exact value depending on several variables including load. In view of these uncertainties, it was decided to assume a 0.7 lagging power factor for the inverter design characteristics, under all load conditions.

The other inverter characteristics adopted in this study were also based on the GE design (Ref. 5). These features included automatic system startup, synchronization, power transfer, load pickup, peak load limiting, and power tracking. The early stage of development of the specific residential on-site inverter system prevents a definition of several of these features in other than qualitative terms. A summary of the assumed inverter characteristics is given in Table 3.1.

3.2 Feedback Power Level

The level and duration of feedback power to the utility was determined through a simple hand calculation comparing the output power of the photovoltaic system with the demand of the residence. The photovoltaic power output was determined on the basis of insolation data and photovoltaic system efficiency values, while the residential demand was obtained from demand data files as discussed below.

The adopted profile for power demand was established by combining data derived from actual measurements with information generated by independent load models that synthesize residential load demand profiles. Figure 3.2 contains examples of residential load profiles for winter and summer seasons in southern California, as measured by a local utility company. These profiles represent the average demand of a relatively large number of houses and consequently show the smoothing effects of house-to-house load

SPECIFIC

OUTPUT VOLTAGE	- 240 V
FREQUENCY	- 60 Hz
FULL LOAD RATING	- 13 kW
POWER FACTOR	- 0.7 LAGGING

MISCELLANEOUS

SYNCHRONIZATION	- LINE FREQUENCY
POWER TRANSFER	- AUTOMATIC UPON PRESENCE OF UTILITY VOLTAGE
TRACKING	- MAXIMUM ARRAY POWER
LOADING	- NOT CONTROLLED
LOAD CHANGE RESPONSE	- 100 ms

Table 3.1. Inverter Characteristics

diversity. Therefore the peak, shown as 3.8 kW, is less than might be observed in the average demand of a smaller group of houses. The time variation of these profiles provides important information that was useful in this analysis. The winter load curve shows a definite morning peak and an evening peak separated by a "valley" at midday. The summer afternoon peak and its duration and magnitude are attributed to the increase in operation of air conditioning units as the afternoon temperatures rise during the summer. The curves in Figure 3.2 are for a specific region and climate. Other areas with different climates will have different load curve shapes. For example, Figure 3.3 shows curves for residential loads in Arizona. The winter season demand curve in Arizona is similar to that of California, but the summer season curve has a considerably more pronounced air-conditioning peak. This difference could produce a somewhat different feedback power level and duration for systems located in Arizona. In this study, the analysis was based on the Southern California load models.

The calculation of the feedback power level was made by subtracting the house demand for a typical single residential unit from the photovoltaic output. A synthetic load profile for baseload appliances developed by GE (Ref. 5) was used as the basis for the residential load model. This profile, in the form of hourly demand, is shown in Table 3.2 and was selected because it appears to properly represent individual baseload residential demand. It does not, however, include temperature-sensitive loads such as space conditioning (heating and cooling), which must be added to the baseload to determine the total residence demand. Space conditioning during summer periods was assumed to require air conditioning. In the GE design, air conditioning is provided by a heat pump, which, for an average Southern California house, would have a full-load power demand of 4.88 kW. All air conditioning units are thermostatically controlled to be either on or off. Therefore, in defining the total individual household demand, the 4.88 kW load of the space cooling unit was added to the baseload demand. The peak demand for the single residential unit then would be 7.21 kW, a value that is reasonably consistent with the 8 kW per house assumed in the design of the distribution circuit.

Figure 3.2. Residential Load Curves, Southern California

Figure 3.3. Residential Load Curves, Arizona

<u>TIME, hr</u>	<u>DEMAND, kW^a</u>
2	0.75
4	0.52
6	0.67
8	1.77
9	1.88
10	1.73
12	1.95
14	1.75
16	1.40
18	1.90
19	2.33
20	2.15
22	1.60
24	0.90

^a Demand includes all appliances, lighting, hot water heating and miscellaneous loads except space heat or cooling.

Table 3.2. Baseload Demand

In the residential demand curve of Figure 3.2, the rise in load during midafternoon was attributed largely to the response of air conditioning units to the afternoon temperature rise. For the purposes of this study, it was assumed that the influence of air conditioning on the shape of the demand curve before that time was minimal and that the time that the air conditioning demand began to be significant was about 3 PM. After 3 PM, the saturation of air conditioning operation, that is, the number of units turned on (but not necessarily operating at one time because of thermostat control) was assumed to be nearly 100%. On the basis of this reasoning, it was decided to add a constant air conditioning load of 4.88 kW to the baseload demand profile during the period between 3 PM and about 10 PM, after which most air conditioning units were assumed to be turned off.

The profile of the output of the photovoltaic system was computed on the basis of the insolation on a fixed, flat-plate array, the value at peak insolation being 13 kW. The shape of the output was assumed to be smooth, neglecting any effects of clouds or other atmospheric condition changes.

The net hourly utility power demand, the result of subtracting photovoltaic output from residence demand is shown in Figure 3.4. The power level curve shows the utility supplying power at about one kilowatt from midnight to about 5 AM, at which time the photovoltaic system begins to produce more power than the load demands, ultimately resulting in a feedback peak of about 11 kW near noon. The feedback declines to zero at about 5 PM, after which the utility begins to supply power, with a peak of about 7 kW. The feedback power, with a peak of about 11 kW, was predicted to exceed the distribution system design value of 8 kW for a period of about 5 hours, beginning at about 8 AM and ending at about 1 PM.

The general impression derivable from the curve of Figure 3.4 is that the photovoltaic system delivers about twice as much energy back to the utility as the utility delivers to the customer. The peak power feedback could, of course, be lowered to match the peak line capacity of 8 kW by

Figure 3.4. Power Interchange Profile for Single Residential Unit

reducing the array size, at the expense of requiring the utility to furnish more energy to the customer. Probably the better strategy would be to include storage in the system and use it to delay the backflow of power until the time of system peak. This could reduce the generation capacity required by the utility. These and other possible ways to tune the system for optimum performance were beyond the scope of this analysis, but might be considered for future work.

Section IV

ANALYSIS OF DISTRIBUTION SYSTEM IMPACTS

Previous sections have discussed the development of the baseline distribution system design, the expected levels of power flow the circuits will experience, and the generalized operating characteristics of the photovoltaic units during both normal and feedback power flow conditions. In this section the effects of feedback power flow on the distribution circuit are analyzed. The effects of faults are also examined and, to a limited extent, the dynamic characteristics of a utility system with photovoltaic units are analyzed. Wherever unacceptable consequences of distribution circuit operation were detected, the appropriate changes were identified in the design or operation of the distribution system which were needed to correct the condition.

In the first part of this section, conditions under steady state normal operation with power feedback are analyzed. In a second section, possible problems under faulted and transient conditions are considered briefly. A third section presents a discussion of dynamic effects. A fourth treats operational aspects of on-site generation, and a fifth deals with the question of metering the power flow to and from the residence.

4.1 Steady State Power Analysis

A summary listing of the equipment and circuit elements that were analyzed, the criteria used in determining whether performance was acceptable, and a description of the proposed solution(s) is presented in Table 4.1.

The baseline radial distribution system is defined in the design schematic of Figure 2.2a and the accompanying specifications in Table 2.2. As indicated, the distribution circuit design was based upon an assumed peak coincident load of 8 kW per house. From the feedback power level analysis in Section 3.2, a peak power level of 11 kW was identified. This increase in power level over normal distribution system peak loads suggests that circuit components will be operating at higher power levels than specified and that some or all of the components of the circuit may be stressed beyond acceptable limits.

A review of all identifiable circuit components showed that in fact some would be overstressed. The capacity of conductors, circuit breaker panels, and meters on the secondary side of the distribution system appear to be adequate. However, overload design factors on the primary side of the distribution circuit were not found to be totally adequate. The primary conductor, consisting of No. 8 AWG copper, will be overloaded by about 7% above its nominal rating of 96 amperes. The overload condition would exist for only about one hour each day, a condition that would probably not damage the circuit. Therefore, this issue was not considered to require a change in the conductor size. Circuit voltage drop under full load operation was also examined but was not considered a problem, since the increase in voltage drop per circuit due to increased current was still well within the assumed criterion of 10 volts/circuit total drop. However, voltage regulation would need to be examined in somewhat greater detail if power factor correction using on-site capacitors were adopted, as is recommended below. The distribution transformers, rated at 100 kVA, would experience an overload condition of about 32% under full load power feedback. Many utilities will

DESIGN ISSUE	EVALUATION CRITERIA	RESPONSE
PRIMARY CONDUCTOR LOAD SYSTEM FULL LOAD CURRENT - 70 A/mi. SYSTEM FEEDBACK FL CURRENT - 96 A/mi.	AWG No. 2 RATED AT 90 A SHORT TERM (1-2 hr) OVERLOAD $\leq 10\%$	NO CHANGE (7% OL)
PRIMARY CONDUCTOR VOLTAGE REGULATION FULL LOAD VOLTAGE DROP - 4.8 V/mi. FULL LOAD FEEDBACK VOLTAGE DROP - 6.7 V/mi.	VOLTAGE DROP ≤ 10	NO CHANGE
DISTRIBUTION TRANSFORMER BASELINE DESIGN - 12 HOUSE/100 kVA (96 kVA/100 kVA) FEEDBACK LOAD - 132 kVA (32% OL)	TRANSFORMER SHORT TERM OVERLOAD $\leq 10\%$	NEXT LARGER SIZE TOO LARGE (338 kVA) BANK WITH 50 kVA TRANSFORMER (not economical) REDUCE NUMBER OF HOUSES TO 10/100 kVA
REACTIVE LOAD SUPPLY INVERTER LOAD POWER FACTOR - 0.7 - 0.8	CIRCUIT SHOULD OPERATE AT ABOUT 0.9 PF	ADD CAPACITORS <ul style="list-style-type: none"> • AT LOAD POINT • ON DISTRIBUTION LINE • AT SUBSTATION

Table 4.1. Equipment and Circuit Impact Analysis Listing

allow transformers to be loaded to 110% of full rated load capacity before taking action to rectify overload conditions. However, a 32% overload will substantially reduce the useful life of the transformer. There are several possible solutions to this problem. One is to upgrade the transformer to the next standard size, which is 333 kVA. Another is to bank each 100 kVA transformer with another transformer. The latter fix would only be economical in a retrofit situation. A better solution would be to serve fewer houses with each 100 kVA transformer. A reduction from 12 to 10 houses would reduce the load on individual transformers to an acceptable level. Of course, under these conditions, two additional transformers would have to be added to each mile of radial circuit.

A major item of potential impact is related to the circuit power factor. If uncorrected, the assumed 0.7 power factor of the inverters would result in a substantial current increase to the circuit, further overloading it to an unacceptable level. Experience has shown that power factor correction is generally to be preferred over operation at low power factor. However, selection of a final operating power factor is dependent upon a number of conditions that must be carefully considered before a selection of power factor can be made. Utilities do apply economic penalties to customers if power factors are excessively low, but they differ as to the exact value of power factor where penalties are applied. However, the range of acceptable power factors is usually between 0.85 and 0.9. Correcting a circuit from a 0.7 power factor to 0.9 requires the addition of 0.536 volt-amperes of reactive power for each watt of real power. This latter requirement was applied in sizing the power factor correction equipment to be added in the case considered here.

4.2 Fault and Transient Analysis

The photovoltaic system considered in this study is designed without any rotating mechanical components. It has no capability for internal storage of energy in either magnetic or mechanical form. Conventional generators use the Hall effect associated with a coil rotating in a magnetic

field to produce electric power. Consequently, they have energy stored in the form of mechanical inertia in their rotating members and also inertial magnetic energy in the magnetic field of the generator. A typical mechanical generator when faulted will produce large quantities of additional current by converting its stored energies into electricity over a short time period. The resulting large currents can be very damaging to equipment and can lead to system problems if not promptly corrected. In the baseline design, this problem will not arise. The photovoltaic system will deliver current to a distribution system fault, but only slightly in excess of rated capacity.

Figure 4.1 shows in schematic form the assumed protection configuration for the photovoltaic system, the customer, and the utility. A circuit breaker (CB_{pv}) provides fault protection for the circuit leading from the main breaker panel over to the photovoltaic system (presumed to be several feet distant from the main panel). Faults within the photovoltaic system would be cleared by tripping of CB_{pv} and the blowing of fuses on the DC input side of the inverter (of point A on the diagram). If the house bus load is less than the available capacity of the photovoltaic system, the direction of power flow will be backward through CB_L toward transformer T_D . Line protection from transformer faults is provided by primary circuit fuses at the transformer. Separate secondary circuit protection is not provided. However, with the type of inverter design specified, the photovoltaic system will purportedly automatically disconnect upon failure of the utility presence signal (line voltage). These two actions would deenergize the line and clear the fault. It is presumed that circuitry internal to the inverter will enable it to differentiate between full load and faulted conditions.

Analysis of faulted circuit conditions shows that only phase-to-phase and phase-to-ground faults merit detailed study. Three-phase faults would not be fed by power from photovoltaic systems since all inverters would be shut down upon loss of the utility presence signal; all phase voltages would be zero in a three-phase fault. The analysis of phase-to-phase and phase-to-ground faults was based on the assumption that the circuit in

Figure 4.1. Single Line Diagram of Protection and Switching Design for Distribution System with On-Site Generation

question is a 12 kV three-phase feeder, delta-connected with a ground fault detecting circuit at the substation. The selection of a delta-connected secondary with loads connected phase-to-phase was considered to be the preferred configuration because of its relative insensitivity to false tripping due to phase loading unbalance and its greater sensitivity to detection of ground faults.

The diagrams of Figure 4.2 and 4.3 further illustrate the system and associated fault protection design. It is assumed that a substantial number of houses equipped with photovoltaic systems would be connected to each of the circuit phases represented by G_1 , G_2 , and G_3 . The Figure 4.2 diagram depicts the conditions of a primary circuit phase b-to-c fault. Voltage loss on phase b-to-c shuts off all G_3 units and effectively shorts the coil of transformer b-c. This places all of the photovoltaic systems on phases G_1 and G_2 in series with internal voltages 120° apart shunted through the line impedance Z_L . By design the individual outputs of the photovoltaic system are current limited. Fault current from G_1 and G_2 units would be dissipated in the line and fault. The power level delivered during the fault from the operating photovoltaic units would be about 6400 kW, corresponding to a current of about 530 amperes. The utility contribution during a phase-to-phase fault at the end of the one mile long radial would be about 1800 amperes. Substation circuit breaker opening times are typically less than 10 cycles, after which time all three phases of the circuit would be deenergized and both utility and photovoltaic system current flow would cease.

On a primary circuit ground fault, as illustrated in Figure 4.3, photovoltaic units on all three phases would continue to operate since utility phase-to-phase voltage would be present at each inverter. The photovoltaic systems would not furnish fault current to a primary circuit ground fault, but would continue to supply the load. Fault clearing would occur with the opening of the substation feeder breaker, at which time the photovoltaic systems would also automatically clear the line upon loss of utility presence signal.

Figure 4.2. Phase-to-Phase Fault

Figure 4.3. Ground Fault

In summary, the analysis shows that fault protection in delta-connected primary systems with photovoltaic units would not present substantially more difficult problems than in conventional distribution circuit design. In fact, it appears that adequate measures are already present with the baseline design to insure the protection of equipment and provide public safety in the event of circuit fault under these conditions.

4.3 System Dynamic Analysis

Stability is an important concept for both conditions of steady state load flow, where power is constant or changing very slowly, and also for transient conditions, where power is changing very rapidly. The transient condition may be caused by the sudden application of load or more often by a fault or by switching. According to an IEEE definition, "Stability, when used with reference to a power system, is that attribute of the system, or part of the system, which enables it to develop restoring forces between the elements thereof, equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements." Furthermore the term "stability limit" is defined as "the maximum power flow possible through some particular point in the system when the entire system or the part of the system to which the stability limit refers is operating with stability." Both of the concepts of stability limits and restoring forces play important parts in the dynamic analyses of a utility distribution system, as discussed below.

For preliminary stability analyses, a simple power system may be visualized which consists of a generator connected to a large system consisting of many other generators and loads, where the output of the generator under observation is small in comparison to the system load and capacity. In this simplified model, the system capacity is commonly considered to be infinite in comparison to the output of the single generator. This simplified analogy of an actual system resembles the configuration, as described in this report, of a small, low-power

photovoltaic generator connected to a larger system of conventional generators. The preliminary evaluation of the dynamics of that simple system included a first order analysis of steady state and transient stability, a subject that the following discussion will attempt to address.

In a motor-generator set of a conventional power plant, power is produced by rotating elements having the physical properties of inertia and angular momentum. When a conventional generator of this type is operated, its massive, rotating element is producing power at the system frequency. The angular momentum of the rotating element allows the generators in the system, through instantaneous changes in system frequency brought about by changes in load, to shift load balances, and hence exchange energy between themselves as electric power according to their individual characteristics. This interchange of load balances and electric energy between generators occurs through the interconnecting transmission circuitry. If undamped, the oscillatory response of the power exchange to the load changes might increase until the capacity limits of system components were exceeded, potentially damaging them permanently and rendering them inoperative. Oscillations of system power level of this nature can be slow, or low in frequency, a condition sometimes referred to as "hunting" between two or more generators. This condition is sometimes the result of incorrect prime mover/governor/generator combinations.

Static inverters constructed with solid state devices, i.e. not of the motor-generator variety, have been postulated for use with the small on-site residential photovoltaic generator systems described in this report to transform the direct current produced by the photovoltaic devices to alternating current power. Electronic inverters of this type do not have the physical properties of mechanical inertia and angular momentum. The rapid response capabilities of the solid state electronics (5-15 μ secs) allow the solid state inverter to adjust to power output changes much more quickly than can conventional generators. The ability of the inverter, in general, to rapidly change output power levels is almost independent of the units' particular electric power capacity, therein differing from conventional

machines whose response characteristics are closely tied to their size as well as their type. Consequently, the static inverter is capable of tracking the requirements of a system's changing power demands very closely and essentially independently from other system parameters, thereby virtually eliminating the oscillatory "hunting" problems associated with the generation of system power.

As stated above, a photovoltaic generator system has the appearance of a simple power system defined by a small generator connected to a large or infinite system. Under steady state conditions, such a system, including the photovoltaic generator with its inverter, may be designed to produce power at a near-constant level (as determined by the control setting of the inverter). It is possible to simplify the stability analysis by making certain assumptions about the characteristics of such a simple system thereby permitting the formulation of some first order observations about the system's steady-state stability. First, to the individual photovoltaic system, the large system appears as a low, near-zero reactance. The utility system has essentially infinite inertia, and its operating voltage remains constant. The inverter has a near-zero inertia, as explained previously, an operating voltage that is nearly constant, and a relatively low internal reactance.

From the basic generator-to-generator power transfer relationships (e.g. Ref. 10), it can be shown that the ability of the inverter to deliver power to the system is inversely proportional to the sum of the reactances of the interconnecting transmission circuit and inverter, and directly proportional to the inverter voltage phase angle, which is defined as the angle between the system voltage and the inverter's internally generated voltage. The latter parameters of inverter reactance and the mechanism for varying the voltage phase angle are functions of the equipment design, as determined by the physics of solid state devices and associated circuitry. The interconnecting transmission reactance is dependent upon the circuit conductor geometry and conductor size and construction. For the photovoltaic generator system discussed in this report, the interconnecting transmission

circuits would be the utility distribution circuits, which are typically of a low-voltage design (4-16 kV), with a close-spaced, parallel cable geometry. Because of the relatively close conductor spacing, the reactance of the distribution circuits is small in comparison to the reactance of the high voltage transmission circuits. In transmission circuits, conductor spacing must be large because of the very high operating voltages. Consequently, for a given conductor size, the closely-spaced geometry of the distribution circuit used in this design to transmit feedback power would result in a circuit with a high power stability limit.

Because of the disbursed configuration of the many small power generators assumed for the photovoltaic generators used in this design, power feedback does not require the use of a high voltage transmission circuit typical of utility systems. Therefore, the circuit configuration proposed in this design will have a relatively low reactance, and hence may have stability limits at least equal to or higher than those of the transmission circuits for conventional generation systems.

The evaluation of the issue of the transient stability of the simple system configuration postulated above requires the examination of the relative response of the photovoltaic generator (inverter) to the infinite system during large and rapid system power changes. As explained above, the rapid transient response of the inverter permits the frequency of its power output signals to be held precisely in synchronism with the system frequency during large power swings. The inertial build up of large stores of energy in the solid-state inverter system is not possible, and unstable oscillatory exchanges of power between the photovoltaic generator system and the essentially infinite system of the utility will not occur. Therefore, transient instability between the inverter and the utility generation system is unlikely.

Systems using solid-state electronic inverters as power generators have an additional feature which is quite unique. The inverter output power regulation of such systems can be designed to be capable of functioning in

several modes. One mode might be with the inverter control regulating the inverter for constant power output (within available array power output levels). Other modes might include having the inverter track the array output as it varies with solar input, or, because of utility system considerations, having the inverter track the residential load. In addition to these features, the inverter could also be designed to track the system frequency and respond with changes in power level according to the changes in system frequency which would occur during a disturbance. These performance features are possible with static, solid-state inverters largely because of their very rapid response capability to power changes. It does not appear that the rapid response characteristics of the photovoltaic system would adversely effect the dynamic characteristics of conventional systems. Rather, it appears that the use of solid-state inverters could substantially benefit overall system performance by helping to stabilize the overall system.

4.4 Operational Analysis

In the system operational analysis, it was assumed that the operation of the utility system with photovoltaic units would satisfy all of the historic criteria regarding public safety. Also, it was presumed that any changes to the distribution system design to accommodate photovoltaic systems should be such as not to impose additional operational burdens on the operating staff of the utility. In applying these guidelines, it was observed that the single largest potential safety issue was that of inadvertent line energizing from photovoltaic system operation during local maintenance procedures. A further examination of the proposed design concept for the inverter output control (main-power-to-utility-line contactor) disclosed that a single malfunction of the electronics controlling the contactor which connects the inverter to the household electrical system, or failure of the contactor itself, could inadvertently energize a deenergized line and possibly seriously injure personnel working on the line. With the baseline configuration, the intended method for operating the system could not positively guarantee that the line would be kept safely cleared during maintenance. Therefore a design fix was needed. Two designs were conceived

and each was considered a satisfactory solution to the safety problem. In one design, a disconnect switch was installed with a key operated lock at the site of each photovoltaic unit. In the second design, a pole mounted disconnect switch was installed on the secondary side of each distribution transformer. The second configuration was adopted as the preferred design because it allowed convenient lineman access to the switch, fewer switches were needed, and less labor and time would be needed to clear a line.

4.5 Metering

The installation of photovoltaic units, on customer property, with the ability to feedback power to the utility introduces the problem of metering. The present utility metering scheme for single-phase customers uses a single-element, single-register meter. The meter is connected so that energy consumed by the customer causes a positive motion of the register dial. If power flow were reversed, as in the case of feedback from the photovoltaic unit, then the meter register dials would simply revolve backwards. The net effect would be that only the difference between utility-supplied power and house-holder feed back power would be recorded. One possible solution to this problem would be to add a detent (register ratchet) to the meter that would allow the meter to record only utility-generated or feedback power, but not both. If both utility-generated and feedback energy records were needed, then a second meter (also supplied with a detent) could be added to the householder's system. The second meter current coil would be wired in reverse to allow it to record feedback power only.

The selection of a metering scheme is, of course, dependent upon billing criteria and hence governed by rules set by the Public Utilities Commission. If billing were to be based on time of day for either utility supplied power, feedback power, or both, then the two meter scheme would not be adequate and other provisions would have to be made. Currently there is no single meter made that would both provide time-of-day metering and differentiate between utility-generated and feedback power. However, some time-of-day meters being developed for residential use could probably be

modified to perform these functions. Meters of new design are available which use a tape recording power demand meter that is capable of measuring demand (utility-generated and feedback) on a reference time basis. Though these devices are available, they cannot be read in the field as can conventional integrating meters. Periodically the meter tape must be removed and decoded on a tape-recorder billing machine. This added complexity would add to the cost of such advanced metering systems.

Section V

COST ANALYSIS

Ultimately, the impact of any proposed modification in design or operating practice of the utility system is a change in the cost of delivering power to the customer. Several previous studies have examined the cost of producing power from photovoltaic devices, for different commercialization scenarios and a wide range of parameters (Refs. 1, 5-9). It was not the intent of this effort to reexamine or extend the results of those studies. Instead, the objective of this study was to critically examine the design and operating impacts of photovoltaic power generation feedback on utility distribution systems, and to quantify these impacts in terms of distribution system costs. This topic was not addressed in the earlier works. Ultimately such costs would be borne by the customer in the rate base. Since the determination of specific energy cost impacts requires a multitude of information regarding future policies of energy pricing which could only be speculated upon at this time, it was not considered appropriate to attempt to estimate incremental energy costs to the house holders. Instead an attempt was made to gain insight into the relative economic impacts of power feedback by examining the differential construction costs associated with the recommended design changes, relative to baseline costs of conventional distribution systems. That approach has provided the basis for judging the economic impacts on utility systems of power feedback from residential customers. It is important to point out that the estimates of incremental costs were made on a per-mile basis, assuming that all houses on

a common distribution radial had a photovoltaic generator. In effect this implies 100% local saturation on a given radial line. In a practical situation, extrapolation of this assumption to the level of the entire distribution substation would be unrealistic because of the mix of residential, commercial, and industrial loads associated with most systems. However, having the cost expressed on a per-mile basis allows the estimate of system impact to be estimated as a scalable function depending upon penetration level. Therefore, results of this analysis may be applicable to many utilities having similar design practices where large numbers of housing units are developed over short time periods.

5.1 Baseline Circuit Cost

The basis for comparing the capital cost of power distribution was the baseline system, defined in Section 2. The cost of constructing the baseline distribution circuit was found to be approximately \$27,000 per mile, in current dollars (1978). The details of the calculation are shown in Table 5.1. In computing the capital cost per mile of the circuit, right-of-way costs were not included because these costs would apply equally to any design case considered. The cost of the service drop and connection was estimated to be about \$156/house, with meter costs of \$35 per house. Thus, the total estimated cost of household hookups was \$20,055 per mile. Household hookup costs have not been included in the estimates of the utility's capital cost of distribution circuits since they are frequently charged to the tract builder and included in the costs of the house to the homeowner.

5.2 Design Change Cost

Three design changes were identified in the analysis of the distribution system which potentially impact the cost of its construction. The changes consisted of the addition of more distribution transformer capacity to handle the increased circuit demand due to feed back from the photovoltaic systems, the addition of secondary circuit isolation switches to allowing safe and efficient line clearing, and the installation of power

	<u>\$/MILE OF CIRCUIT</u>
1. DISTRIBUTION CIRCUIT	
POLES, 35 POLES / mi. @ \$359.64 / POLE	12,587
CONDUCTORS, $\frac{5280 \text{ ft / mi.}}{1000}$ @ $\frac{\$182.93}{1000 \text{ ft}}$ (3)	2,898
TRANSFORMERS, $\frac{840 \text{ kVA / mi.}}{100 \text{ kVA / UNIT}}$ @ \$1342 / UNIT	11,276
TOTAL	26,761
2. SERVICE DROP	
CONDUCTORS AND INSTALLATION, 105 HOUSES / mi. (\$156 / house)	16,380
3. METERING	
WATT HOURS METER, 105 @ \$35 / METER	3,675
TOTAL DISTRIBUTION CIRCUIT SERVICE COST	\$46,816

Table 5.1. Baseline System Costs

factor correction equipment in the form of capacitors. Of these, the power factor correction was by far the most expensive at \$29,484/mile. Additional transformer capacity would increase costs by \$4227/mile and an increment of \$2280/mile would be needed for secondary disconnect switches. The total incremental cost impact was estimated to be \$35,991/mile. Details of the cost calculations are shown in Table 5.2.

The exact economic impact of necessary metering changes cannot be estimated at this time, as explained earlier, without a definition of specific rate and billing criteria. However, on the basis of information in Section 4, data were compiled from the Sangano Instrument Company on the prices of various metering options that might be considered. The prices of four meter options were established, including the currently popular class 1, single-register units. The costs are shown in Table 5.3. It is rather apparent from the table that the requirement for any type-of-time of day metering, either with or without feedback, will add a significant amount to the initial installation cost of electric power service.

5.3 Evaluation of Relative Impact of Cost Increase

The relative cost increase of all design modifications, about \$36,000/mile when costs of metering are not included, was found to represent a 133% addition to the baseline distribution circuit cost of about \$27,000/mile. This value was established by comparison to the distribution circuit costs in Table 5.1, item 1. As previously noted, the service-drop and meter costs were not included in the incremental capital cost estimates because they are not universally borne by the utility and are sometimes included in tract construction costs paid by the tract contractor and eventually by the homeowners. If power factor correction is excluded from the reckoning (perhaps by assigning this cost to the photovoltaic system), then the cost increase is 24% per mile. Both accounting methods represent substantial increases in distribution circuit costs. However, in the perspective of the entire utility, circuit construction costs represent only a fraction of the overall distribution costs. The dominant cost item in

\$/MILE OF CIRCUIT

1.	ADDITIONAL TRANSFORMER CAPACITY	
	$\frac{1155 - 840}{100 \text{ kVA}}$ kVA / mi. @ \$1342 / mi.	4,227
2.	LOW SIDE DISCONNECT SWITCH	
	11.4 SWITCHES / mi. @ \$200 / SWITCH	2,280
3.	POWER FACTOR CORRECTION	
	105 HOUSES / mi. (7.02 kVAR / house) @ \$40 / kVAR	29,484
	TOTAL COST CHANGE	\$35,991

Table 5.2. Design Change Cost

	<u>UNIT COST, \$</u>
1. 1-PHASE SERIES 200 WATTHOUR	35
2. 2 1-PHASE WATT HOUR WITH DETENTS	90
3. 3 REGISTER TIME-OF-DAY WATT HOUR	380
4. DIGITAL DEMAND, MAGNETIC TAPE	410 ^a

^aTape decoding equipment additional cost @ \$80,000.

Table 5.3. Metering Costs

distribution is the substation. Construction costs for urban-sited, distribution substations are typically \$250/kVA. Therefore the substation investment for a 6000 kVA feeder similar to that of the baseline design in this study is \$1.5 million. When applied against each mile of feeder, the substation investment is about \$215,000 per mile. When substation costs are included, the increase in construction costs over total distribution investment for all design changes is about 15% per mile. This latter comparison perhaps more properly places the impact in proper perspective with other system cost elements. While a 15% cost impact cannot be considered trivial, consideration has not been given to the economic benefits accruing to the utility from the sale of the feedback energy, which would offset the added capital costs of the distribution system. A substantial amount of revenue could be earned from the operation of photovoltaic systems with feedback, particularly if time-of-day feedback rates in excess of utility-supplied power rates were adopted. These impressions are apparent from a casual examination of the power curve of Figure 3.3. Additional study and analysis would be necessary to confirm this conclusion.

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